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PHYSIOLOGICAL METHODS IN ASTRONAUTICS

By

R. M. Bayevskiy

FOREIGN TECHNOLOGY DIVISION

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PHYSIOLOGICAL METHODS IN ASTRONAUTICS

BY: R. M. Bayevskiy

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R. M. Bayevskiy

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TABLE OF CONTENTS

PART I

PHYSIOLOGICAL MEASUREMENT AND INFORMATION SYSTEMS

PART II

METHODS PHYSIOLOGICAL RESEARCH

U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH

DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

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PREFACE

One of the most complex and, at the same time, extremely important, problems of space medicine and biology is the collection and transmission of information on the condition of an astronaut at a great distance from Earth. This problem is interlaced with the ideas, interests, and methods of various disciplines: radio electronics and medicine, psychology and automation, physiology and cybernetics. In distinction from physicians and physiologists, who work in ground laboratories, specialists in space medicine are forced to be concerned with a large number of limiting factors such as weight and size restrictions, power consumption of on-board medical equipment, limitation of the number of telemetering channels, recording time and carrying capacity of channels, and limitations related to the prolonged location of electrodes and transducers on the body of an astronaut. Practically none of the known physiological methods can be applied under the conditions of space flight without an appropriate modification, and in a number of cases it is necessary to develop fundamentally new methods.

The monograph by R. M. Bayevskiy illuminates a wide range of problems related to achievements in the area of methods for obtaining biomedical information from outer space. The author is a specialist in space physiology and a direct participant in Soviet space research. In summarizing the development of the methodological area of space physiology, R. M. Bayevskiy spends considerable time on the perspectives of physiological measurements in future, longer and further, and also interplanetary, flights. Here, from strictly scientific positions, many questions for the first time are considered and discussed, which until now were the objects of hypotheses and scientific fantasy. General ideas and concrete solutions tested by experiment

and under clinical conditions are described, which convinces the reader not only in the reality of the practical guarantee of safety of further, more complicated, space flights, but also in the expediency of the recommended solutions.

The first steps of space medicine were closely related to the application of traditional well-known research methods (with the appropriate modernization), and the subsequent development of this area proceeded in its own, original ways. The book strongly emphasizes this process of the transition from conventional methodological presentations to new concepts stipulated by the specific nature of space flight, as well as by the present status of science and technology, the advent of cybernetics and automation, and the serious application of quantitative methods in medicine and biology. In addition, it was evident that many of the solutions dictated by the nature of space research could not be practically applied on Earth. Therefore, R. M. Bayevskiy's book should be useful not only to specialists working in the field of astronautics, but also for the extensive group of physicians, physiologists, engineers, and mathematicians interested in the problems of collecting, disseminating, and processing medical information.

The book constantly emphasizes the presence of "feedback" between the problems of space medicine and practical health. In both cases the main problem is to ensure the well-being of the "patient." It is natural that the use of the achievements in space medicine for improving the medical service of the population is an important scientific and social problem.

R. M. Bayevskiy's book illustrates the necessity of extensive education of the physician and physiologist in the most diverse areas of contemporary science and technology, and we hope that it will be received with interest by the readers.

V. V. Parin and O. G. Gazenko

INTRODUCTION

"Science moves in leaps and bounds, depending upon the progress made by the methodology. With each step of the methodology we rise one level higher, which opens up to us a wider horizon with previously invisible objects."

(I. P. Pavlov)

On 4 October 1957, the Soviet Union launched the first artificial earth satellite (ИСЗ) [AES] in the world. This event began a new age in the history of man's conquest of nature. The broad perspective of interplanetary and space flights, knowledge of the planets of the solar system, and study of the Universe was expended. But the conquest of space is impossible with the aid of only a few automatic instruments, let alone even the most perfected. It is necessary that the master of the spaceship and outer space, and then the planets, be man.

On 3 November 1957, the second Soviet artificial earth satellite was launched into orbit with a living being on board, i.e., the dog Layka. This flight was the beginning of systematic biomedical investigations in space, which in a little more than three years led to an outstanding victory of Soviet and world science — the circumterrestrial orbital flight of pilot-astronaut Yu. A. Gagarin in the "Vostok" spaceship.

In the realization of these and subsequent achievements, a significant role was played by space biology and medicine — a new science with an extremely diversified range of problems and tasks. A characteristic of space biology is its close contact with the other natural and technical sciences: physics, chemistry, astronomy, aerodynamics, and radio engineering.

N. M. Sisakyan, V. V. Parin, V. N. Chernigovskiy, and V. I. Yazdovskiy [234] thus defined the basic scientific problems which make up the subject space biology:

1. Study of the influence of extreme factors of outer space on living terrestrial organisms.

2. Investigation and development of the biological bases for ensuring space flights and life on the planets.

3. Study of the forms and conditions of extraterrestrial life.

A more detailed examination each of these problems is contained in the works of N. M. Sisakyan [232, 234, 236, 238], N. M. Sisakyan, O. G. Gazenko, and A. M. Genin [233, 237], O. G. Gazenko [78], and other authors.

The birth and development of the new science also stipulated the emergence of new research methods to ensure the obtainment of the necessary experimental data, their interpretation, and analysis [49, 199, 201]. The flight test as the basis of space biology and medicine advanced biological telemetry as its main method, i.e., long-distance measurement of various biological indices.

The large number of data recorded in a space flight and in various laboratory investigations demanded the creation of special data-measuring systems which, on the basis of the latest achievements of science and technology, would provide quantitative measurements.

The collection, transmission, recording, and processing of the huge volumes of information necessary for the development of space biology and medicine requires the extensive use of the methods and facilities of radio electronics, automation, and cybernetics.

New methods are necessary not only for providing biomedical investigations in flight, but also for carrying out special laboratory experiments on Earth.

A very essential condition is the compatibility of the results of ground and flight tests; therefore, it is extremely important that in both cases the same methods be used as much as possible. Certainly, under laboratory conditions there are possibilities for expanding the range of procedures by employing methods which cannot be used in a spaceship, but the condition of compatibility of the obtained results with the flight-test data should also be observed in this case.

One of the most important problems of space biology and medicine consists in studying the influence of extreme factors of outer space on living organisms. The development of research in this direction led to the origin of an independent division in space biology, i.e., space physiology. Space physiology studies an

extensive range of problems related to the study of the state of various physiological systems and organs during the action of extreme factors, investigation of tolerance limits, development of methods for increasing the resistance of the organism, clarification of the mechanisms of pathological reactions and ways of compensating them, problems of the interaction of the organism with the medium, and others. Space physiology is closely related to such areas of space biology and medicine as space psychology [93], space hygiene [156], space microbiology [116], and also other disciplines, e.g., aviation physiology, radiation medicine, and others.

The tasks of the preparation and realization of manned space flight, which has recently occupied a central position in Soviet space biology and medicine, necessitated the extensive development of physiological research and, at the same time, the introduction of physiological methods into astronautics.

A systematic account of the experience of physiological measurements under space-flight conditions has hampered the dynamic nature of this scientific endeavor. New ideas, instruments, and experimental data appear daily, which attempt to satisfy the ever increasing demands of astronautics. The huge number of publications on space biology has already led to the necessity of compiling special bibliographic publications in this field [539]; not less extensive are the publications concerning the methods of physiological research in reference to the accomplishment of space flights. Bearing in mind that the methods of space physiology are being developed to a definite extent on the basis of already known methods, one should also try to estimate the expediency of using in astronautics the various physiological methods that are applied in other areas of medicine. The expediency and necessity of these works is mentioned in a recent report concerning a U. S. Air Force contract with the RCA Service Company for a study of the feasibility of employing electronic methods for purposes of physiological monitoring in aviation and astronautics [373].

Soviet space physiology presently has the most experience in physiological research. The huge volume of valuable physiological information obtained from artificial earth satellites and spaceships during flight experiments with animals and the flights of our astronauts is a result of the development and improvement of physiological methods in astronautics. The value of physiological methods in realizing the first manned space flight has been stated repeatedly in the works of N. M. Sisakyan, V. V. Parin, O. G. Gazenko, V. I. Yazdovskiy, and others [199, 233, 235, 73]. An important role was played by physiological methods in providing

reliable medical monitoring during the flights of Yu. A. Gagarin, G. S. Titov, A. G. Nikolayev, P. R. Popovich, V. F. Bykovskiy, and V. V. Nikolayeva-Tereshkova [5, 10, 32, 38, 49, 78, 195, 294, 295], and also the crew of the multiseater "Voskhod" spaceship.

The monograph attempts to generalize five years of operational experience in the area of physiological measurements in space (1959-1964) from the point of view of the physician-physiologist. The contemporary achievements of astronautics to a considerable extent are the result of collective efforts. An especially important role in space physiology was played by the collaboration of physicians and engineers. The successes attained became possible only due to the friendly work of physiologists, designers, mathematicians, and all the scientific and technical personnel that participated in the preparation and performance of biomedical investigations in space. Therefore, in all cases, where it is possible, references are made to published materials or persons who have worked on the question in point are indicated. Along with the data collected in the USSR, information from foreign research is also discussed.

Physiological methods in astronautics are considered in relation to the general biological problems of space research and certain aspects of space technology. The term "physiological methods" in this case implies not so much the specific methodological procedures (for instance, electrocardiography or pneumography), as the principles of accomplishing physiological measurements under space-flight conditions. The monograph discusses, in sequence, data on the physiological methods that have already been used in previous experiments, contemporary methods, and the perspectives of their development. In examining the perspectives of such a rapidly developing science as space physiology, we had to make a careful selection of data that had already been documented in various scientific publications.

The monograph consists of 11 chapters. The historical outline of physiological space research which comprises the first chapter serves as a necessary prerequisite to the following presentation of physiological methods.

The first part of the monograph (Chapters 2-6) "Physiological Data-Measuring Systems" is devoted to general questions of physiological measurements in space flight. The main purpose of this section consists in examining the methods and facilities of space physiology in reference to flight experiments. The concept of the physiological data-measuring system emphasizes the four leading aspects of the problem: physiological — directed towards the solution of its own physiological

problems; measurement — based on the quantitative evaluation of physiological processes; informational — which considers the various physiological data as signals which carry on the processes occurring in an organism. Finally, the aspect which emphasizes the necessity of applying a complex of various facilities united into a single system that is intended for the solution of a specific problem, in this case for physiological measurements. The physiological data-measuring system here is considered as a particular case of the biological data-measuring system.

The second part of the monograph (Chapters 7-11) "Physiological Research Methods" considers the specific physiological methods that are used in astronautics. Prime attention is given here to the methods which have been employed in flight experiments with animals and in manned flights; however, considerable space is also a... oted to methods that have been developed in reference to future space flights.

The bibliographic index includes more than 800 sources. This was stipulated by the multitude of monographs and the necessity of considering questions related to biology, technology, and cybernetics. The invention of new instruments and methods for space research was initially directed basically towards adapting the already existing methods to new conditions. This also is now an important trend in space physiology. However original, purely "space," solutions have appeared quite rapidly, which make it possible to significantly increase the reliability and effectiveness of the research. These "space" solutions, in turn, are beginning to enter "terrestrial" medicine and public health.

The profound interrelation of various close and remotely-connected branches of knowledge is characteristic for contemporary science. This interrelationship is accomplished on the principle of "feedback," when an intensive exchange of information, ideas, and experimental data serves as an important stimulus of scientific and technical progress. A good example of this type of feedback is the use of "terrestrial" methods in space and "space" methods on Earth. The achievements of space physiology in the area of collecting and processing information are of serious value for extensive medical practice since the problems of diagnosis, control, and prophylaxis cannot be solved effectively without contemporary radio-electronic instrumentation methods. This, in particular, is the important role of space biology and medicine which both are common to science and to humanity.

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CHAPTER 1

BRIEF HISTORICAL OUTLINE OF PHYSIOLOGICAL SPACE RESEARCH

Space flights are a natural result of scientific and technical progress. An historical survey of physiological space research makes it possible to trace the onset and development of objective methods of collecting biomedical information and to explain the main trends of their further improvement. The survey presents data that pertain only to in-flight investigations. The survey consists of four sections which are devoted to aerostats, aircraft, rockets, and spaceships, respectively.

Physiological Investigations in Balloons and Aerostats

A balloon was the first means by which man went into the air, and then the stratosphere. There is information that the first balloon flight in the world was made by the Russian inventor Kryakutny in Ryazan in 1731 [228]. More detailed data are published about flights in balloons designed by the Montgolfier brothers. On 19 September 1783, in Paris, a sheep and a duck ascended to a height of about 500 meters in one of these balloons [328]. Two months later, on 21 November 1783, the French scientist Pilâtre de Rozier and a companion, Marquis d'Arlandes, ascended to a height of about 1 km. The first unfavorable altitude effect during a flight in an aerostat (19 December 1783) was experienced by the French scientist Jacques Charles [372].

On 4 June 1784, a balloon flight was made for the first time by a woman, Madame Thible. The height of her ascent was about 3 km. On 7 January 1785, an American physician, Jeffrey [sic], and an Englishman [sic], Blanchard, made a balloon flight from England to France. The first reputable publication on the influence of balloon flight on the human organism is accredited not to a physician, but a journalist, Baldwin, who in 1786 published a scientific work under the title

"Aeropedia."

By the beginning of the 19th century there appeared many reports by physicians and scientists about their flights in balloons, which laid the foundation for the development of aviation medicine as a science. One of the first balloon flights for scientific purposes was made at St. Petersburg on 12 July 1804 by a physicist, Academician Ya. R. Zakharov. On 24 September and 1 October 1805, the Russian physician Kashinskiy made an ascent in an independently built balloon. We know of the flights of some eminent scientists of that time, Robertson, Bay-Lussac, and Biot, who described the symptoms of altitude sickness (hypoxia) in a balloon ascent.

As the altitude of balloon flight increased, manifestations of altitude sickness became dangerous for the outcome of the flights. Thus, on 5 September 1862, the director of the Greenwich Observatory, James Glaisher, and a scientist by the name of Coxwell, nearly died from acute oxygen starvation: their balloon reached an altitude of 8800 m and both aeronauts lost consciousness several times. Glaisher's observations are of much interest since his ascent to this altitude without oxygen equipment is, most likely, the only one. Glaisher noted changes in skin color, difficulty in breathing, afferentia disturbance, and other phenomena. All this demonstrated the need to pay more attention to the preparation of subsequent flights. Further steps in the conquest of altitude are linked with the name of the famous French scientist Paul Behr, who established that disorders in a high-altitude ascent are caused by a lack of oxygen and proposed to take oxygen supplies on a high-altitude flight. Of importantance to the development of high-altitude physiology was the work of the famous Russian scientist I. M. Sechenov [228].

On 15 April 1875, there took place a flight in the balloon "Zenith," which carried a small supply of oxygen. The balloon reached an altitude of about 8000 m. The aeronauts, Tissandier, Crocé-Spinelli, and Sivel, could not use the oxygen because they developed euphoria. Only Tissandier was saved, who later described this state. In the flight of the "Zenith," which was organized with the participation of Paul Behr, attempts were made to conduct planned medical investigations. It was proposed to measure pulse rate, respiration rate, and body temperature. The equipment for the in-flight physical measurements included a barometer, thermometer, and spectroscope [378]. Because of the tragic outcome of the flight, this program was not carried out. Nineteen years later, in 1894, the German scientist Berson, using the scientific results of research on oxygen deficiency made a successful ascent to an altitude of about 9000 m in an open gondola. He had oxygen supplies

and heating facilities. In 1901, Berson and Züring, in a specially built giant balloon, ascended to an altitude of over 11,000 m. A large role in the development of aeronautics was played by the great Russian scientist D. I. Mendeleyev. He ascended by himself in an aerostat to an altitude of up to 3000 m. D. I. Meneyeleyev is credited with the idea of using pressurized cabins for high-altitude flights.

A new series of flights in balloons with closed (airtight) gondonas was initiated in the 1930's. In 1932, the Swiss scientists Piccard and Cosyns ascended to an altitude of almost 18 km, and in 1933, the Soviet stratonauts Prokof'yev and Godunov ascended to an altitude of 21 km. One year later there occurred the flight of Fedoseyenko, Vasenko, and Usykin, who reached an altitude of 23 km in the stratosphere balloon "USSR-1". The Americans Stevens and Anderson ascended approximately the same altitude in 1935.

Balloon flights at the end of the last century were of importance to research on the influence of decreased barometric pressure on the human body, and the flights in the 1930's played a significant role in the development of means for protecting man in a high-altitude flight. Pressurized cabins, air-conditioning and heat-control systems, and pressure suits were developed and tested. However, none of these flights made it possible to obtain any significant objective physiological information inasmuch as at that time the means of telemetry for physiological and biological data had not yet been developed.

In the 1950's, aerostats were used by American scientists for research in space medicine. They studied the influence of cosmic rays and the "feeling of isolation," checked out model of high-altitude equipment and devices. Experiments were conducted by the Air Force in the "Manhigh" program (three flights) and by the Navy in the "Stratolab" program (four flights) [328]. The highest altitude (approximately 33 km) was reached in the aerostat Manhigh II in August 1957. There are also reports that in 1960 an ascent was made to an altitude of approximately 37 km.

The application of methods of biological telemetry in the indicated experiments with transmission of physiologic information to Earth made an essential contribution to the development of intrumentation methods of space medicine. Thus, the aerostat Stratolab V contained medical equipment for recording 12 physiological parameters [722].

We should mention the use of aerostats for conducting biological investigations. The Soviet Union in 1938 carried out a biological experiment with Drosophila flies in

the stratosphere balloon "USSR-1," which ascended to an altitude of 15,300 m [86]. Experiments with the exposure of various biological specimens (dogs, mice, microbes, plants, insects) in the United States have been conducted regularly since 1947. In a number of cases the biological experiments were, in a sense, a rehearsal for a manned flight. So, Project Manhigh conducted two flights with mice and guinea pigs to check out the capsule and equipment. On 9 July 1960, the aerostat "Astro-60-8," with a tissue culture, Chlorella, and bacteria, reached an altitude of approximately 48 km. This is a unique record for an high-altitude flight of biological specimens in an aerostat.

We should further note the aerostat flights conducted by Project "Excelsior." This project is anticipated an aerostat ascent with a subsequent parachute jump from an open gondola. In 1959-1960, an American pilot by the name of Kittenger made three jumps from altitudes of 24, 26, and 34 km. This event included radio-telemetric recording of pulse and respiration, and also radio communications during free fall; these parameters were simultaneously recorded by a self-contained automatic recorder on the parachute [661]. Similar investigations have a direct bearing on improving safety equipment and instruments for monitoring the astronaut's condition during his descent to Earth.

Physiological Investigations with Airplanes

The first heavier-than-air craft in which a manned flight was made was an airplane designed by A. F. Mozhayskiy. This historical flight, which began the development of modern aviation, took place in Krasnoye Selo, near St. Petersburg, in the summer of 1882. The beginning of the 1900's witnessed the rapid development of aeronautical engineering all over the world. On 26 June 1906, Blériot made the first flight across the English Channel. In 1913, a Russian pilot, P. Nesterov, made the first acrobatic maneuver in an airplane by performing a "loop". Airplanes were employed in World War I as a means of combat. The improvement of aircraft hardward, which continuously went on between World War I and World War II, made it possible to achieve a large number of successes by the beginning of the 1940's. The non-stop crew flights of Valeriy Chkhalov and Mikhail Gromov across the North Pole to America, the record-breaking flight of the aviatrices (P. Osinenko, V. Grizodubova, M. Raskova), and the flights of Soviet pilots to the North Pole are known the world over.

Aviation in World War II was one of the most important branches of the armed forces. Jet aircraft appeared at the end of the war. The first jet aircraft was tested in the USSR at the end of the 1930's.

Together with the development of aviation, aviation medicine was developed which was then one of the important sources of space medicine. Many of the problems of space medicine are traditional divisions of aviation medicine: for instance, the influence of G-loads on the human body, and the effect of decreased barometric pressure and severe vibrations. Of importance to the development of aviation medicine was the work of the Soviet researchers V. V. Strel'tsov, A. P. Appolonov, N. M. Dobrotvorskiy, G. Ye. Vladimirov, P. I. Yegorov, L. A. Orbeli, and others [160, 228].

The airplane is presently being used in practical space medicine as a means of creating brief weightlessness for special investigations and for astronaut training. A proposal concerning the use of Kepler's parabola for creating brief weightlessness in an aircraft was published by F. Haber and H. Haber in 1950 [493], and in 1951 the first such flight was made by an American pilot, S. Crossfield. Subsequently, several such flights were made in the USSR, the United States, and other countries (Italy, France, Argentina). An aircraft also was used as means of simulating the conditions of orbital entry and descent to Earth. For this purpose, the influence of weightlessness was studied after the G-loads created during aircraft motion on a "dive spiral" or by the G-load created after a flight on a Keplerian parabola preceding it [326]. In distinction from experiments involving submersion into water [478, 479], where physiological effects similar to those obtained in weightlessness could be studied only partially, or from experiments with the aid of a "reduced-weight tower" [605] or an elevator [101], where the duration of weightlessness was too short to cause shifts in the state of the vegetative functions which correspond to the zero-gravity state in a spaceship, the airplane was an important instrument for research as well as for astronaut training [516].

In accordance with the Soviet astronaut training program, training flights in airplanes specially equipped for reproducing the conditions of weightlessness had the following goals [294, 295]: familiarization of astronauts with the zero-gravity state and determination of their individual resistance: study of the physiological functions in the zero-gravity state and in transient periods.

The following recordings were made in flight by means of on-board automatic recording devices: electrocardiogram, respiratory rate, arterial pressure, and motor coordination (hand-writing analysis and conditioned-motor responses). The

duration of the period of weightlessness amounted to 45 sec. In the initial and final periods of parabolic flight there appeared G-loads of 3.5 ± 0.5 units. In these flights, the possibility and quality of the reception and transmission of speech under conditions of weightlessness was investigated and astronaut activity was filmed.

In analogous flights conducted in the United States, electrocardiograms and galvanic-skin reactions were investigated. Films also were made [326]. F-105 aircraft were employed to record electrocardiograms, arterial pressure, respiration and, in certain cases, body temperature and galvanic-skin reactions. Simultaneous transmission of data by telemetry was accomplished [513, 678]. It is interesting to note that certain methods were first tested in airplanes which were then used on a spaceship: for instance, impedance pneumography [513]. The American rocket plane X-15, which is designed to climb to an altitude of up to 80 km with a speed of approximately 6000 km/hr for the purpose of monitoring the pilot's condition, was equipped to conduct telemetric transmission of pulse rate, respiratory rate [451], body temperature and suit pressure [465].

Thus, physiological investigations in airplanes made it possible to obtain the first information on the action of accelerations and weightlessness, and also to check the effectiveness of a number of research methods. It was established that during the creation of brief weightlessness there can appear vegetative and sensory disturbances. These phenomena are encountered five times less frequently in persons having flight experience [139]. It was also pointed out that during the intermittant influence of accelerations and weightlessness there can occur regular shifts in the circulatory, respiratory, and central nervous systems [132].

Physiological Investigations with Rockets

Balloons, aerostats, and airplanes made it possible for the scientist to gain the experience of high-altitude flights and to become acquainted with some of the dangers standing in the path to space. However, the only means of studying outer space at the present time is the rocket. Therefore, investigations with rockets marked the beginning of the practical development of astronautics and made it possible to carry out the first biomedical experiments in space.

Rockets served as military weapons in ancient times. There is a legend about an attempt to lift a man into the air with the aid of several rockets ignited simultaneously; naturally, such an attempt could not have a safe ending [448]. The

first flight of a living being in a rocket took place at Paris in 1806. A gunsmith named Ruggieri successfully launched a rabbit which safely descended to the ground on a parachute, but this flight was neither based on scientific calculation nor good luck. Only after almost 150 years later could Ruggieri's experiment be repeated.

The Russian revolutionary Nikolay Kibal'chich was the first to design a rocket ship for space flight. In 1883, from his prison cell, he wrote his scientific testament, which was discovered in the archives of the police department only after the Great October Revolution. It is interesting to note that the principle of the rocket platform which was proposed by N. Kibal'chich was used in project "Orion" by the U. S. Air Force in 1960 [648].

The first large-scale work that contained the scientific foundation of the applicability of jet engines for space flight was written by K. E. Tsiolkovsky: "Investigating Space with Rocket Devices." The first chapters of this work were printed in 1903 in the journal "Scientific Review" and only in 1911 did its continuation appear in the journal "Herald of Aeronautics". K. E. Tsiolkovsky is rightfully considered to be the founder of scientific astronautics. His works anticipated many contemporary discoveries and inventions. The theoretical research and experimentation in the field of jet propulsion which was conducted in the twenties and thirties in our country (N. A. Rynin and F. A. Tsander) and abroad (H. Oberth in Germany, R. Goddard in the United States, and Esnault-Pelterie in France) made it possible to construct the first rockets — the prototypes of future spaceships. Work on rocket weapons which were employed in World War II, was an important stage in the development of astronautics.

The first biomedical experiments with rockets, which were initiated by American researchers in 1946, used captured V-2 rockets. On 17 December 1945, at the Wright Field proving ground, the first launching of a V-2 rocket was conducted with a capsule containing mushroom spores to an altitude of 183 km. However, the capsule was not found after the flight. On 20 February 1947, American scientists were able to recover a capsule containing fruit flies from altitude of 109 km. Then four V-2 rockets were launched with monkeys onboard. The first attempt to send an animal into space was made on 11 June 1948 (project "Albert I"). However, this attempt ended in failure. The second experiment ("Albert II") took place on 14 June 1949. Although the monkey died (during landing), valuable data were obtained by means of radio-telemetry on the pulse and respiration of the animal during the entire flight

to an altitude of 140 km. In this flight, physiological data were transmitted for the first time to Earth from on board a rocket by means of radio-telemetry. The third experimental V-2 flight again was a failure, and finally, in the fourth flight (in the summer of 1950) they succeeded in studying the motor responses of intact mice with the aid of a camera which was actuated in specific time intervals.

In 1951, American researchers began to use "Aerobee" rockets for biological experiments. Three launchings were made with monkeys, which were under narcosis, and mice: the first and second launchings, in the summer of 1951, were failures; the third launching, on 21 May 1952, was made with two drugged monkeys and two mice. The monkeys, Pat and Mike, were the first primates which the American scientists were able to recover alive and unharmed from a flight to an altitude of approximately 60 km. The results of the biological investigations on the V-2 and "Aerobee" rockets are summarized in an article by Henry, Ballinger, Maher, and Simons which was published in 1952 [575]. The authors noted the important role which was played by the application of radio-telemetry methods for physiological investigations. Despite the fact that more than half of the missiles were demolished when they fell to the ground due to a failure in the parachute systems, valuable scientific information was obtained owing to the use of radio-telemetry.

At approximately the same time, the Soviet Union conducted vertical rocket launchings with various animals (dogs, rabbits, rats). The presence of a very reliable landing system made it possible to perform most of the recordings with the aid of automatic recorders on board the rocket. In certain cases, physiological data were also transmitted by telemetry. From 1950 through 1957 three series of experiments were conducted. The first series was devoted to a study of the survival rate of animals under the conditions of a small capsule during flight to an altitude of up to 110 km. In the second series they studied the feasibility of applying pressure suits and recovering animals by means of ejection with subsequent descent on a parachute. Finally, the experiments of the third series were distinguished by an increase in the altitude of ascent to 212 km, wherein one of the two dogs was sent on a flight in a state of narcosis [53].

In 1958, the flight altitude was increased to 450-475 km owing to the application of ballistic rockets. Many animals accomplished several flights in rockets. The dog Otvazhnaya made five flights.

In 1959-1960, ballistic rockets were launched with dogs and rabbits. Problems of the influence of weightlessness on muscular tonus and motor coordination were first investigated in them. The data obtained as a result of the described experiments made it possible to estimate the physiological reactions of the animal organism to a weightless state lasting several minutes after the preceding action of accelerations, and also the action of accelerations (launching) following weightlessness [77, 54, 83, 33, 134, 154].

After a six-year break, the American biological experiments with rockets were renewed in 1958. Van der Wall and Young organized the launching of three "Thor-Able" rockets whose nose cones each contained a mouse. The flight altitude was over 2000 km and the duration of weightlessness was approximately 45 minutes. None of the capsules were found; however, as a result of the application of radiotelemetry in the second and third rockets, data were obtained on the pulse rate, respiratory rate, and arterial pressure of the animals.

On 13 December 1958, the United States launched a "Jupiter" rocket whose nose cone contained a capsule with a monkey called Gordo (genus saimiri). The flight altitude was 470 km, the time was approximately 15 minutes, and the duration of weightlessness was 7.8 minutes. An important role was also played here by telemetering systems, by means of which the transmission of physiological data was accomplished. Although the container with the animals also did not return to Earth, the experiment was not a failure since valuable scientific information was obtained.

The second "Jupiter" flight with two monkeys, Able (genus rhesus) and Baker (genus saimiri), took place on 28 May 1959. In this flight the duration of the period of weightlessness amounted to 4.2 minutes. Telemetric recording of electrocardiograms, pneumograms, electromyograms, phonocardiograms, and body temperature was performed, and the behavior of the animals was filmed. The hygienic parameters of the biocapsule were recorded; temperature, pressure, and gas composition of the air. The animals were recovered alive and unharmed from the flight [481, 449].

At the end of 1959 (4 December) a successful launching of a chimpanzee, Sam, to an altitude of 90 km was made. This launching was carried out under project "Hermes" in order to prepare for the flight of astronauts under project "Mercury." The purpose of project "Hermes" was to develop an escape system for a manned capsule [483].

An American program of preparation for launching a man into space, known as project "Mercury", was initiated in October 1958. The general management of this

program was assigned to the National Aeronautics and Space Administration (NASA). The "Mercury" program foresaw the construction of an inhabited capsule for a twenty-four-hour orbital flight, first a ballistic flight, and then an orbital manned flight with identical takeoff and landing regimes [570, 788, 789]. The mentioned launching of the chimpanzee Sam on a "Little-Joe" rocket in a "Mercury" capsule was the first experiment in the American man-in-space program. A subsequent analogous flight with Sam was conduced on 21 January 1960. Finally, the last launching of an animal in a "Mercury" capsule before a manned flight took place on 31 January 1961. This was the chimpansee Ham, who ascended to an altitude of approximately 200 km in a "Redstone" rocket; the period of weightlessness lasted for 7.5 minutes [334, 500, 451, 312].

The first suborbital (ballistic) manned flight was carried out in the USA on 5 May 1961, i.e., almost one month after the first Soviet orbital space flight in the world. The Americ astronaut A. Shepard stayed in flight for 15 minutes; weightlessness lasted a little more than five minutes; maximum flight altitude was 187.4 km. The splash-down site was the Atlantic Ocean, 486 km from the launch site (Cape Canaveral, now known as Cape Kennedy). Physiological data (electrocardiogram, respiration, and body temperature) were recorded by means of radiotelemetry.

A second American balli--ic flight, similar to the first [788], was made by V. som on 21 July 1961.

In the project "Hermes" flights, the first studies of psychomotor activity of primates were made, whereby disturbances in their efficiency during takeoff and landing were discovered, and attempts to record vectorelectrocardiograms also were made [483].

To complete the survey of physiological investigations with rockets, we should mention the French experiments. In February 1961, a "Véronique" rocket was launched with a white rat, Hector. By means of chronically implanted electrodes, they recorded brain, reticular-formation, and neck-muscle potentials, and also pulse and respiration. The telemetry system functioned until the moment of separation of the first stage during the descent, after which recording was performed by a self-contained on-board recorder. At the end of 1963, a similar experiment was repeated with a cat, Felix [475, 476].

Biomedical experiments with rockets provided space biology with abundant information on the influence of flight factors on an organism, and made it possible

to develop methodological bases for subsequent investigations with artificial earth satellites. The American scientists used ballistic rockets to prepare for manned space flight. The first American astronauts did not accomplish orbital, but suborbital flights.

In Soviet Union, on the basis of improved rocket technology, it became possible, earlier than in the United States, to transfer from biological experiments with rockets to experiments with artificial earth satellites, and then directly to the realization of the first orbital space flight in the world.

Physiological Investigations with Artificial Earth Satellites and Spaceships

On 3 November 1957, the Soviet Union launched a pressurized capsule with a dog, Layka, into the orbit of an artificial earth satellite. This experiment was a natural continuation of the investigations that were conducted by Soviet scientists with rockets. When setting up the biomedical experiment with the artificial earth satellite, it was necessary to solve a number of complicated problems on the construction of automatic life-support equipment for an animal which would function for a sufficient period of time (air-conditioning, heat-control, feeding systems, and others). It was also necessary to design scientific equipment for transmitting the results of physiological observations to Earth. Figure 1 shows a picture of the dog Layka, the first living being to orbit around the globe.

The following physiological parameters were recorded during the flight: electrocardiogram, pneumogram, arterial pressure in the carotid, and actogram. The physiological equipment was automatically controlled from a programmed device [263].

Fig. 1. Layka – the first living being to orbit around the Earth.

As a result of the first flight experiment in the Earth's orbit, space biology obtained a number of important facts, some of which confirmed the previous observations and others brought out new questions. This flight demonstrated the possibility of the survival of a highly organized living being during entry into the orbit of an artificial earth satellite and in orbital flight. It also demonstrated the important role of biotelemetry inasmuch as,

despite the fact that the satellite could not be returned to Earth, valuable information was obtained on the influence of flight factors on physiological functions. However, the question concerning the reactions of a living organism to the accelerations which appear during descent remained unclarified. Similar investigations were possible only with recoverable artificial earth satellites.

On 19-20 August 1960, the USSR conducted the first flight experiment in the world with one return of animals from space to Earth. The possibility of comparison of the pre- and post-flight data with the results of in-flight physiological was a serious scientific achievement which was related to the use of radiotelemetry. The large range of physiological methods that were employed for studying the dogs Belka and Strelka provided the basis for calling the second Soviet satellite ship a "flying laboratory."

This first successful experience of setting up extensive physiological investigations in space was one of the important stages in the development and formation of space medicine and biology.

In December 1960 there took place a new flight experiment — the flight of the third Soviet satellite ship with the dogs Pchelka and Mushka on board. The ship entered an uncalculated orbit and ceased its existence during re-entry; however, owing to the application of telemetering systems, valuable scientific information collected. Thus, from the biologist's point of view, this flight was quite cessful since it deepened the knowledge on the physiological state of animals under conditions of multihour existance in weightlessness.

In 1961, which was the first year of the space age, the fourth and fifth spaceships were launched with the dogs Chernushka and Zvezdochka on board. These flights preceded the triumphant flight of Yu. A. Gagarin which took place on 12 April 1961. A new system of physiological measurements was tested which was specially developed for reliable medical monitoring of the state of the basic vital functions of an astronaut [193]. The first manned space flight, as we know, opened a new page in the development of space biology and medicine. It was also the first check-out of a medical-monitoring system in a space flight.

The first manned space flight was an outstanding achievement of Soviet and world science. This flight opened the road to the further conquest of outer space and to new manned space flights (Fig. 2).

On 6 August 1961, the USSR launched the "Vostok-2" with pilot-astronaut G. S. Titov on board. During this twenty-four-hour space flight, dynamic medical

monitoring of pulse and respiration was conducted, for which electrocardiograms and pneumograms were transmitted through telemetering channels. In addition, the mechanical work of the heart (kinetocardiography) was investigated. For operational medical monitoring sound signals corresponding to pulse rates were continuously sent through a "Signal" shortwave radio transmitter.

On 11-15 August 1962, the USSR conducted the first multi-day group space flight of the astronauts A. G. Nikolayev and P. R. Popovich in the "Vostok-3" and "Vostok-4." This flight was a new and important achievement in space technology and space biology. A large program of physiological measurements was carried out during the flight, which included, in addition to recording electrocardiograms and respiration, the recording of biopotentials of the brain, eye movements, and galvanic skin reactions. Experience was gained in medical monitoring during the performance of a multi-day group space flight, and also in solving a number of research problems in the performance of a manned space flight.

On 14-19 June 1963, there took place a group flight by the astronauts V. F. Bykovskiy and V. V. Tereshkova in the "Vostok-5" and "Vostok-6." The program of physiological measurements this time was expanded by means of the application of seismocardiography, i.e., a method of studying the contraction function of the myocardium. Of importance was the experience received in setting up physiological investigations for the flight of a woman.

12 October 1964 will be entered in the history of astronautics as the beginning of a new age in the manned conquest of space. On this day the Soviet Union launched a three-man spaceship, the "Voskhod," into a satellite orbit. In addition to the pilot-astronaut, a scientist and a physician went on flight for the first time. This was the first space expedition in history, a prototype of the scientific expeditions which will be made to the Moon and the planets, and for working in manned stations in space. The inclusion of a physician in the crew was very noteworthy. A young colleague of one of the scientific-research institutes became the first space physician. In this flight the duties of the

Fig. 2. Yu. A. Gagarin — the first astronaut in the world.

ship's physician included not only problems of prophylaxis, but the rendering of medical aid if necessary. The physician participated in the solution of many scientific problems. He controlled the research equipment and conducted a number of measurements himself with the aid of the on-board instruments. During the flight of the "Voskhod" many new physiological methods of collecting biomedical information were tested. Methods of dynamography and recording of written-language signals for studying the efficiency and state of precision motor coordination were employed for the first time. The first experiment in the programming of medical investigations was carried out. The flight had an important methodological value since it made it possible to check out a number of theories concerning the organization of collective work of a crew in a spaceship.

Table 1 gives the basic data on Soviet biomedical orbital experiments beginning with the flight of Layka.

The first attempt at an orbital flight of a space capsule with biological specimens was made by the Americans in June 1959. They prepared for the flight of four black mice on a "Discoverer", but the "Atlas" rocket did not send the satellite into orbit [328].

On 12 September and 7 December 1960, the satellites "Discoverer-17" and "Discoverer-18" were launched with capsules containing bacteria spores, cell and 'ssue cultures, plants, and others. In both cases the capsules were recovered in e air as they entered the 31st and 48th revolutions, respectively.

In 1960-1963, American scientists worked on the fulfillment of project "Mercury," the purpose of which consisted in carrying out a twenty-four-hour manned space flight.

As already pointed out, the first stage of project "Mercury" involved the performance of a suborbital flight. After the flights of A. Shepard and V. Grissom, the American scientists began to prepare for an orbital flight. On 29 November 1961, an "Atlas" rocket launched a "Mercury" capsule into orbit with a female chimpanzee, Enos.

The first American manned orbital flight took place on 20 February 1962. Astronaut John Glenn made three revolutions around the Earth and landed safely in the Atlantic Ocean. The duration of flight amounted to 4 hours and 20 minutes. In-flight recordings were made of electrocardiograms, respiration, body temperature, and arterial pressure. Because of the equatorial orbit, the spaceship passed over the same telemetric receiving stations in each revolution. This ensured the possibility of practically constant monitoring of the astronaut's state [789].

Table 1. Basic Data on Soviet Biomedical Investigations with Artificial Earth Satellites and Spaceships

Designation of spacecraft	Research subject	Data of launching	Number of revolutions	Initial orbital parameters, km		Physiological research methods
				Apogee	Perigee	
2nd Soviet artificial earth satellite	Dog, Layka	3.XI 1957	–	1671	225	EKG, pneumography, actography, arterial oscillography
2nd Soviet satellite ship	Dogs, Belka and Strelka	19.VIII 1960	16	339	306	The same + phonocardiography and measurement of body temperature
3rd Soviet satellite ship	Dogs, Pchelka and Mushka	1.XII 1960	17	265	187.3	The same + electromyography and seismocardiography
4th Soviet satellite ship	Dog, Chernushka	9.III 1961	1	248.8	183.5	EKG, pneumography, sphygmography
5th Soviet satellite ship	Dog, Zvezdochka	23.III 1961	1	247	178.1	The same
Pilots-Cosmonauts						
"Vostok"	Yu. A. Gagarin	12.IV 1961	1	327	181	EKG, pneumography
"Vostok-2"	G. S. Titov	6.VIII 1961	17	244	183	The same + kinetocardiography
"Vostok-3"	A. G. Nikolayev	11.VIII 1962	61	251	183	EKG, pneumography, electroencephalography
"Vostok-4"	P. R. Popovich	12.VIII 1962	48	254	180	Electro-oculography, investigation of galvanic skin reactions
"Vostok-5"	V. F. Bykovskiy	14.VI 1963	81	235	181	The same + seismocardiography
"Vostok-6"	V. V. Tereshkova	16.VI 1963	48	233	183	The same + seismocardiograpny
"Voskhod"	V. M. Komarov, K. I. Feoktistov, B. Yegorov	12.X 1964	16	409	178	Electrocardiogram, pneumography, seismocardiography electroencephalography electro-oculography, recording of written signals

During 1962-1963, four orbital space flights were conducted under project "Mercury" (Table 2). The last one continued for 32 hours [790].

The biomedical experiments with artificial earth satellites and the flights of the Soviet and American astronauts made it possible to collect extensive information for playing the scientific foundation of space biology and medicine and space physiology. An extremely important role in obtaining the necessary information was played by the system of objective recording of physiological data and the methods of biological telemetry. It would not be an exaggeration to say that the achievements of space technology could be used for manned space flight only owing to the development of methods which provide reliable monitoring of the astronaut's state under space-flight conditions.

Each science is characterized by its own specific methods and a unique methodology. The brief historical survey given above shows that the methodological basis of space biology and medicine is made up by flight experimentation and its methods involve the measurement of various quantities at a distance under complex and unique conditions that are quite different than on the ground.

The realization of physiological investigations in the field of astronautics can be divided into three stages [6] (Fig. 3): a theoretical study of the problem; laboratory investigations on the ground; flight experimentation.

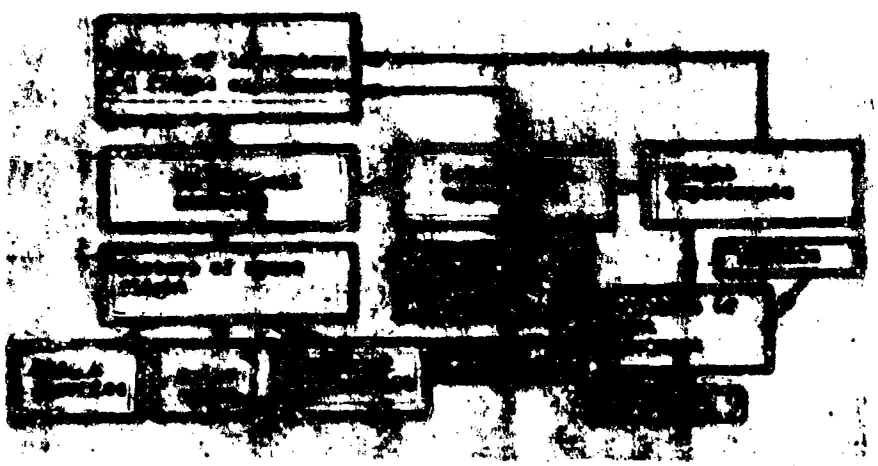

Fig. 3. Stages of biomedical investigations in space.

The results of flight experiments, in turn, play an extremely important role for correcting the old and developing new theoretical concepts [64]. New hypotheses and theories lead to the organization of new laboratory investigations and then to flight experiments. The "feedback" between the flight experiments on the one hand, and the laboratory investigations and theories on the other hand,

provides a dialectic cause-and-effect unity of extensive and diversified investigations which characterizes modern space biology and medicine. One of the instruments for providing this feedback are the physiological methods. They methodologically unite all stages of space investigations into a single process which is governed by a specific idea, i.e., directed towards the obtainment of new information which is necessary for the further development of science.

The leading role of method and methodology which is emphasized in this survey indicates the necessity and expediency of documenting the data collected in this area to the present time. The absence of similar documentation in world literature and the rapid rate of development of astronautics make this task extremely important and timely.

Table 2. Stages of the American "Mercury" Program

Conditional designation	Date, years	Who was in the capsule	Type of flight	Orbital parameters, km		Physiological research methods
				Apogee	Perigee	
MR-2	31.I 1961	Chimpanzee, Ham	Ballistic	203.8	—	EKG, pneumography, measurement of body temperature
MR-3	3.V 1961	Astronaut A. Shepard	The same	187.1	—	The same
MR-4	21.VII 1961	Astronaut V. Grissom	The same	190.8	—	The same
MA-5	29.II 1961	Chimpanzee, Enos	Orbital (two revolutions)	237.2	159.3	The same
MA-6	20.II 1962	Astronaut J. Glenn	Orbital (three revolutions)	261.2	161	EKG, pneumography, arterial oscillography, measurement of body temperature
MA-7	26.VII 1962	Astronaut S. Carpenter	The same	268.7	160.9	The same
MA-8	9.XII 1962	Astronaut W. Schirra	Orbital (nine revolutions)	273.1	161	The same
MA-9	15.V 1963	Astronaut G. Cooper	Orbital (22 revolutions)	267.1	161.6	The same

Note: MR — "Mercury" capsule, "Redstone" launch vehicle; MA — "Mercury" capsule, "Atlas" launch vehicle.

P A R T   I

PHYSIOLOGICAL MEASUREMENT AND INFORMATION SYSTEMS

CHAPTER 2

TRANSMISSION OF PHYSIOLOGICAL INFORMATION FROM SPACECRAFT TO EARTH

One of the essential peculiarities of space physiology consists in the fact that for collecting the necessary scientific information it is forced to use long-distance methods of measurement. The new scientific field (biological telemetry) that emerged in the last decade takes on even greater significance in astronautics each year. In turn, astronautics to a considerable extent assists the great progress being made in the field of biotelemetry. In astronautics it became necessary for the first time for physiologists to contend with the necessity of strict coordination of the volume of transmitted information with the carrying capacity of the telemetering links. This conditioned the application of "information theory" to the consideration of signals of biological origin. Finally, the presence of the large number of objects taking part in the measurement process (source of information, on-board equipment, telemetric devices, physician – recipient of information, and others) conditioned the application of the concept of a "measurement and information system" in space physiology [287]. The great value of this concept will be demonstrated later. This chapter combines the problems of biotelemetry, information theory, and measurement systems, which have a direct relation to questions of the transmission of physiological information from a space craft to the ground.

Biotelemetry

Biological telemetry is the long-distance measurement of biological data. In a broad sense, the sphere of biotelemetric measurements takes in the investigations of various types of biological specimens as well as the recording of data on the conditions to which these specimens are subjected.

There wire telemetry and radiotelemetry. Wire telemetry began with Einthoven's experiments in 1906 on the transmission of an electrocardiogram from a clinic to a laboratory to distances of up to 1.5 km [414], and also with the telephonic stethoscope designed by Brown in 1910, which provided for the transmission of pulse signals to a distance of approximately 150 km [360]. However, space physiology has employed mainly telemetering methods, i.e., methods based on the transmission of physiological data by radio. In the following discussion we will consider namely this method of biological telemetry. The transmission of physiological information by radio was accomplished for the first time by Soviet researchers A. A. Yushchenko and L. A. Chernavkin in 1932 [285]. They recorded signals from a contact transducer which had been adapted to measure salivation through the fistula in a freely moving dog. The same contact transducer was used by these authors for recording working movements in studies on the psychophysiology of work [286]. In 1938 K. Zemlyakov, D. Ivanov, and T. Fedorov transmitted heart tones through wires from a person located in a pressure chamber, and made attempts to record phonocardiograms by radio [119]. The use of radio electronics and, in particular, radiotelemetry in biology obtained especially extensive propagation after World War II. Experiments on the long-distance transmission of physiological data were renewed. In 1948, Fuller and Gordon recorded the sphygomogram and respiration of a freely moving animal by radio istances of up to 30 m [438, 446]. In 1947-1953, the solution of questions of e radio transmission of biopotentials of the human heart and brain was studied by Holter [446, 455, 529] and Parker [446, 351, 651].

In 1948, O. J. Boxer and his colleagues created the first telemetering device for long-distance investigation of the latent period of motor response under conditions of wireless communications and a changing distance between the experimenter and the subject of investigation [51].

In 1952 there began to appear publications about the application of biotelemetry in aviation and space medicine. According to Smith [722], the first experiment with the telemetric transmission of an electrocardiogram from an aircraft was carried out in 1952 in Switzerland. In the United States, the first physiological recordings by means of radio from an aircraft were made in 1953 under project "RAM". The following parameters were transmitted to the ground: electrocardiogram, electroencephalogram, respiration, and body temperature [722]. Subsequently there were special investigations devoted to biological measurements in an aircraft [227, 324, 454]. Many of the publications pertain to the transmission of physiological data

from X-15 aircraft [465, 687, 688].

In 1952 the works of Henry and his co-authors were published on telemetric recording of physiological functions during flights of V-2 and "Aerobee" missiles [375]. However, the first radio transmission of data on biological specimens from a rocket was conducted in 1946 [500].

In the following years biological telemetry began to be applied in the most diverse areas of biology and medicine [471, 194, 205]. Biotelemetric investigations in athletic medicine and the physiology of work have been conducted since 1955 in Sverdlovsk under the direction of V. V. Rozenblat [216]. Long-distance recording of various data in the physiology of agricultural animals has been conducted since 1956 by B. V. Panin [188]. In 1957 there appeared the first publications about the application of telemetering methods for studying pressure, temperature, and acidity in the stomach and intestines [425, 615], and material were also published in the same year on the radio-recording of cellular potentials from the cortex of a non-anesthetized animal [463, 464]. 3 November 1957 should be noted as the birthday of space biotelemetry, when the transmission of physiological and hygienic data from an artificial earth satellite was performed for the first time.

In 1958, Webb and his co-workers recorded the electrocardiogram of a freely moving animal for the first time [768]. This was followed by work on the use of biotelemetric methods in a cardiological clinic [296], in pediatrics [279], in hygienic investigations [97, 98, 386], and other areas [128].

The First Symposium on the Application of Biotelemetry in Medicine and Physiology took place at Sverdlovsk in 1959 [215, 292]. In December 1963 the Second Symposium on Biological Telemetry was also held there. The achievements of Soviet science in the field of space biotelemetry were specially noted at that time [12, 192]. In 1963 the United States held a conference on questions of the application of biotelemetry in animal physiology and ecological research [531, 543].

At the present it is possible to speak of biological telemetry as fully developed scientific discipline. In spite of its nominally great age, biotelemetry can be rightfully called a new scientific field since only in the last 5-10 years, in view of the rapid development of radio electronics, the appearance of semiconductor devices, methods of microminiaturization of equipment, and new radiomaterials, did the creation of various types of equipment for long-distance recording of biological data become possible [104, 386, 242, 279, 325, 310, 323, 406, 446, 530, 549]. An important role in the development and formation of biotelemetry was played by

astronautics. Biotelemetry is gradually becoming an important research method with extraordinarily broad prospects of application in the most diverse areas of medicine and biology.

For remote measurement of various indicators, a complex of facilities called a biotelemetric system is used. The general form of such a system can be represented in the form of a block diagram composed of the following elements: transducers and amplifiers, coders (commutators and modulators), shaping and memory units, a transmitter, a receiver, decoders (converters, commutators), and recorders [543, 744]. As compared to the devices utilized for recording physiological functions under laboratory conditions, the complexity of biotelemetric systems is evident (Fig. 4).

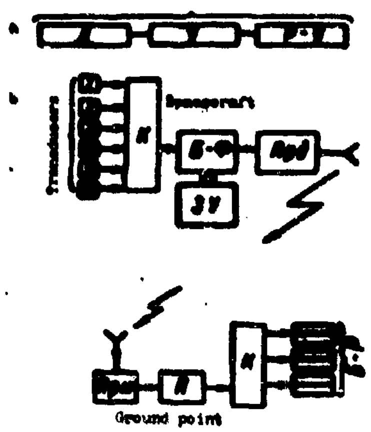

Fig. 4. Block diagram of a laboratory facility (a) and the biotelemetric system of a spacecraft (b).
Д) transducers; У) amplifiers; Р-У) recorders; К) commutators; Ф-Д) telemetric signal shaping unit; ЗУ) memory unit; $ПР_Д$) transmitter; $П_{PM}$) receiver; Д) converter; Б-Р) recorder block.

The attempt to construct a scientific classification of biological telemetry systems is contained in many works. Holter [531] propose to classify biotelemetric systems by the principle of recording time, activity of the subject under investigation, and the urgency of obtaining the data.

He distinguishes the following characteristics of biotelemetry systems:

A_1 — brief recording;

A_2 — prolonged recording;

B_1 — recording conducted during active behavior of subject under investigation;

B_2 — recording conducted from a motionless subject;

C_1 — recording with rapid data analysis;

C_2 — recording with data storage for subsequent analysis.

As a result of various combinations of the indicated criteria, eight variations of biotelemetric systems can be obtained. For instance, system $A_2B_1C_1$ provides prolonged recording with rapid data analysis from a moving subject.

Johnston [548] proposes three types of biotelemetric systems: 1) for investigations of pilots and astronauts, 2) for clinical investigations, and 3) for experiments with animals.

One of the most detailed classifications was proposed by V. V. Rozenblat [216]. He distinguishes five forms of biotelemetry: on-board, dynamic, relay, stationary, and endoradiosonde methods. This classification is based primarily on the consideration of only the biotelemetry methods which have practically obtained application. An on-board system is a biotelemetric system which is characterized by the fact that the investigated subject and the transmitter are both on board a specific object (aircraft, spaceship, and also a motor vehicle or boat) which is traveling with respect to the researcher and the receiver. Dynamic biotelemetry is characterized by the investigation of a freely moving subject, such as an athlete, who carries a transmitter and goes about his usual activity. The combination of on-board and dynamic biotelemetric systems, one of the variations of which may be considered to be intracabin telemetry on a spaceship (for details, see Chapter 4), was called relay telemetry by V. V. Rozenblat. The endoradiosonde method is characterized by the introduction of miniature radio transmitters into body cavities. Stationary biotelemetry, according to V. V. Rozenblat, is the radio transmission of physiological data from one ground point to another with the transmitter and receiver motionless relative to one other.

In 1963, V. V. Parin and R. M. Bayevskiy [198] proposed a classification of biotelemetric systems founded on the consideration of the following characteristics: location of elements of the biotelemetric system with respect to the subject under investigation; circuits and design features; purposes and areas of application of the biotelemetric system.

This classification was substantiated in detail in a special work in 1964 [192], and then composed the foundation of the official classification that was worked out by the commission of the Second All-Union Symposium on the Application of Radiotelemetry in Medicine and Physiology (V. V. Rozenblat took part in this work), which will be mentioned later.

Classification of Biotelemetric Systems

I. According to the interrelation of the subject under investigation, the transmitter, and the receiver:

1) the relative position of the subject under investigation and the transmitter:
   a) transmitter located a short distance from the subject;
   b) transmitter directly on subject;
   c) transmitter inside subject;

2) interrelation of transmitter and receiver: 0 – transmitter and receiver mutually stationary; 1 – transmitter or receiver moving.

Note: Temporary designations of some of the most wide-spread systems at the present time: "stationary" – A0; "on-board" (portable) – A1; "relay" – B0 or V0; "dynamic" – BJ (BJ); "endoradiosondes" – B1 (B1) (capsules and pills).

II. According to area of application.

The investigated systems of the organism (radiopulse background, radio-encephalograph); the branch of biology and medicine (sports biotelemetry, space biotelemetry).

III. According to technical criteria.

Method of information transmission (radio, wire communications, light); method of supplying power to transmitter (self-contained, inductive); method of transmitter control (manual automatic); modulation method; number of channels, and so forth.

Space biotelemetry is presently based mainly on the use of systems of type A1; however, in future it will also employ other types of systems (see below). The characteristic features of space biotelemetry:

transmission of information over very long distances; discrete nature of transmission, which depends on the orbital parameters and geographic location of the receiving stations; limitation of carrying capacity of channels; use of on-board memory units for information storage; simultaneous transmission of a large number of measured parameters; one necessity of collecting information under conditions of normal activity of astronaut; the necessity of operational analysis of part of the transmitted information for purposes of medical monitoring of astronaut.

The features of biotelemetric systems in astronautics conditioned the appearance of a considerable number of special investigations [12, 27, 32, 192, 433, 533, 553]. The serious value of biotelemetry in space physiology is noted in a number of special survey works and monographs [78, 741, 788]. The value of telemetry in astronautics is indicated by the publication of a special handbook on space telemetry by the U. S. in 1963 [804].

In a report devoted to the first manned space flight, Academician A. A. Blagonravov [49] pointed out that space biotelemetry played an extremely important role in providing for medical monitoring of the astronaut's condition, and noted the importance of the further development of work in this field.

Transmission of Physiological Data from the Standpoint of Information Theory

Inasmuch as weight and power consumption of telemetering equipment on board a spaceship are severely limited, the transmitter power and frequency band, and consequently, the amount of information transmitted to the ground, must be coordinated with duration and range of flight. Astronautics is probably the first field in physiologists had to contend with the necessity of such a rigid limit with respect to the characteristics of information, and this in turn demanded the performance of special calculations and investigations.

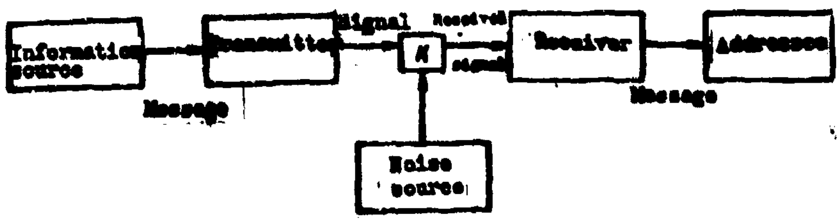

Fig. 5. C. Shannon's communication channel (1948). [K = channel].

First of all we shall consider some general concepts concerning communication channels [52, 710] which make up the basis of telemetering systems. Figure 5 shows a block diagram of a generalized communication channel designed by C. Shannon. The communication channel can be represented in the form of five elements.

1. The information source. In space biotelemetry this is the subject of measurement: human, animal, or controlled medium.

2. Transmitter. This element should be considered as the total of all on-board facilities, including the information collection system, the amplifying equipment, and the telemetering system, which provides for the creation of a signal that can be transmitted through the communication channel.

3. The channel is the medium which is utilized for transmitting a signal from the transmitter to the receiver. The channel is usually characterized by the power, frequency band, and amount of noise; therefore, the noise source is considered together with the channel.

4. Receiver. This unit takes in the entire complex of facilities for reception, amplification, and conversion of signals into a form that is suitable for interpretation by medical personnel.

5. The information recipient, i.e., the ground medical staff.

Thus, the communication channel, as part of the communications system, serves for the transmission of messages from the information source to the recipient. In space biotelemetry the messages are basically considered to be physiological information. Any message is a complete group of signals which characterize the various possible states of the information source. Here we come into contact with the difficult problem of interpretation in terms of the general communication theory of physiologic information, i.e., the parameters, indicators, and curves which we repeatedly record in laboratories.

The concept of information in physiology bears a clearly expressed semantic character. The physiologist and clinical physician are first of all interested in the content of the report they have obtained, regardless of the method of its expression. For instance, information on the presence of tachycardia in a patient can be obtained by counting the number of heart contractions when taking his pulse, by auscultation, by an electrocardiogram, and by a phonocardiogram. The value of the information depends on the previous amount of knowledge about the information source. Thus, the manifestation of tachycardia in a patient with decompensated heart failure will not be unexpected by the physician. Conversely, tachycardia in a healthy person will force the physician to be on the alert and make additional investigations. This means that in the second case the information was more valuable to the physician, or, as it is usually expressed, he obtained more information. Questions of the study of the content or value of information make up a special division of information theory. In the investigation of problems of data transmission, the main objective is not the content of the message, but the number and character of the signals which must be transmitted, and the duration of the transmission. Each message is considered as one of the possible ones which generally can originate from the given source of information. For a quantitative appraisal of information, it is necessary to know the total number of possible signals at the channel input and the probability of appearance of each of them. The concept of amount of information is the corner stone of the information theory. The analysis of information concepts is a complicated philosophical problem. Information is essentially one of the properties of matter. Information theory is concerned with the quantitative description of this property of matter [245].

The first person to point out the possibility of quantitative analysis of information was R. Hartley [506]. The emergence of information theory as a science

is credited to the American mathematician Claude Shannon [710], who in 1948 published his work "The Mathematical Theory of Communication", which today still remains a classic work on information theory.

One of the central positions in this information theory is occupied by Shannon's formula for determining the amount of information (H):

$$H = -n \sum_{i=1}^{m} P_i \cdot \log_2 P_i$$

This formula indicates that the amount of information is equal to the product of the number of signals n times the sum of the products of the probability of each of them multiplied by the probability logarithm. The minus sign is specified by the relationship of the concepts of information and entropy. As it is known, entropy — one of the concepts of statistical mechanics — is a measure of the disorder of a system, a measure of chaos.

The concept of information is the reverse of the concept of entropy since it signifies a measure of organization, of order. Shannon's formula emphasizes the probability character of information. Indeed, in the process of obtaining information, the observer (researcher) in the beginning does not know the state of the object under observation, and then, by observing the obtained signals, receives an answer to the question of the state of the object. Thus, physicians at a telemetry receiving point have a feeling of uncertainty in their knowledge about the state of an astronaut in flight until they obtain the first messages from the spacecraft which is flying in the zone of coverage of the receiving system. Consequently, the obtainment of information may be identified with the elimination of uncertainty. Thus, the presence of the minus sign in Shannon's formula becomes intelligible.

One of the definitions of the amount of information states: the amount of information is a measure of the uncertainty which is eliminated [245]. Prior to obtaining a message, a physician on the ground can assume, with different degrees of probability, the presence of various states of an astronaut. If it is known that during the preceding communication the state of the astronaut was good and no shifts were observed in the other indicators, it is most probable that his state also will be good in the forthcoming communication. The probability of the appearance of syncopal states in this case is extremely small. The probability of the manifestation of symptoms of vestibular stimulation is more significant. It is clear that the probability approach to information is completed grounded and realistic.

However, concerning the question of the transmission of physiological parameters (recordings of physiological functions), it is necessary to temporarily reject the probability approach since we cannot determine the probability of individual signals with sufficient accuracy, the totality of which makes up a message on a physiological parameter. In other words, we still do not know the probability characteristics of the signals which make up the electrocardiograms, sphygmograms, pneumograms, or other physiological messages. Only therefore are we forced to consider all the transmitted signals to be equiprobable and to use Hartley's formula to calculate the amount of information in physiological parameters instead of Shannon's formula, which is a particular case of Shannon's formula in the event of equiprobable signals.

$$H = n \cdot \log_2 m$$

where H is the amount of information, n is the number of signals in a unit of time, and m is the number of possible signals.

Actually, if pi = 1/m, i.e., if the signals are equiprobable,

$$\text{then} - n \sum_{i=1}^{m} pi \log_2 Pi = n \sum_{i=1}^{m} \frac{1}{m} \log_2 \frac{1}{m} \log \frac{1}{m} = n \cdot \log_2 m.$$

The unit of the amount of information is the bit (from the English words "binary digit"). One bit is the information obtained in a single selection from two equiprobable signals. Correspondingly, a single selection from four equiprobable signals gives two bits of information, and selection from 32 signals gives five bits. In other words, the number 2 is employed as the logarithm base when using the formula for computing the amount of information.

To investigate the possibility of transmitting physiological information through telemetering channels it is first of all necessary to determine the amount of information to be transmitted.

Actually, it is a question of the so-called capacity of the information source, i.e., the amount of information which is created by the source of information per unit time. We are solving a similar problem for the first time in reference to physiology, and therefore we shall subsequently devote prime attention to the fundamental approach to the calculation, and not to the achievement of its maximum accuracy. This is also connected with the fact that as we study the probability structure of physiological signals the final computed values will change.

The first attempts to determine the amount of information in physiological parameters were published by the USSR in 1961-1962 in cooperation with V. V. Parin

and O. G. Gazenko [32, 81, 191, 196]. F. I. Bushmin published a work in 1963 [57] in which he considers the reliability of information which is recorded by contemporary electrocardiographs, and uses the concepts of information theory to do this. To explain the speed of creation of information it is necessary to know at least two quantities: the number of possible signals and the minimum necessary number of signals per second. Although physiological parameters are practically continuous functions, they can be completely determined by a sequence of discrete signals inasmuch as the quantization errors can be reduced to a minimum by the appropriate selection of the frequency of readings [710, 759]. Thus, the calculation of the capacity of a physiological source of information amounts to th determination of the number of discrete values for each parameter per unit time (second) which are necessary for a sufficiently complete (in reference to concrete problems) description of a continuous quantity by a series of discrete quantities. It is necessary to determine the quantization rate with respect to two indicators, i.e., time and amplitude. Figure 6 illustrates the quantization alternatives of an electroencephalogram, pneumogram, and electrocardiogram at various frequencies with respect to these two indicators. It is evident from the figure that in time quantization with a frequency of 100 per second all three parameters are well defined by their discrete values. At a quantization frequency of 10 per second, only the pneumogram can be physiologically evaluated, and only delta-waves can be determined in the electroencephalogram. Analogous relationships also occur at different frequencies of amplitude quantization. In determining the quantization frequency, the maximum amplitude of the curve is assumed to be 100% and then quantized with an accuracy of 5 and 20%, i.e., 20 and 5 amplitude readings.

It is not difficult to see that the number of time readings is no other than the quantity n in the Hartley formula, and the number of amplitude readings is the quantity m. Consequently, after determining these values for each physiological parameter subject to transmission by telemetry, we will find a very important characteristic of the communication channel, i.e., the capacity of the source of information. However, this task not as simple as it seems at first glance. The fact is that the selection of quantities m and n depends on the point of view of the physician and the physiologist on the obtained message. If, for instance, a physician is interested in an electroencephalogram only for the presence or absence of delta-rhythms (for the purpose of monitoring sleep and waking cycles), the selection of values of m and n within the limits of 10 and 10, respectively, is

sufficient, i.e., the time quantization interval can amount to 0.1 sec, which is sufficient for manifesting oscillations with a frequency of 2-4 cps, and the accuracy of amplitude quantization can amount to 10%, since it is well known that slow delta-oscillations usually have amplitudes of the order of 20-30 microvolts [114], and therefore, at a maximum amplitude of 100 microvolts they can be easily determined.

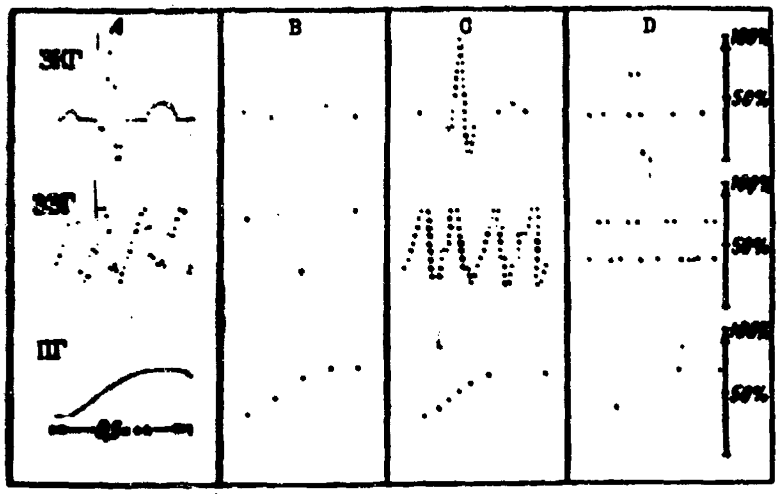

Fig. 6. Example of quantization of an electrocardiogram (ЭКГ), an electroencephalogram (ЭЭГ), and pneumogram (ПГ) with respect to amplitude (A and B) and time (C and D). The accuracy of amplitude quantization is 5% (C) and 20% (D); the frequency of time quantization is 100 and 10 per sec (A, B).

In general, the selection of the frequencies of time quantization for physiological parameters can be based on the Kotel'nikov theorem, according to which the quantization frequency should be twice as much as the maximum signal frequency.

Thus, by knowing the spectrum of the frequencies to be transmitted through a radio channel, it is easy to determine the necessary quantization frequency. It has already been said that the selection of quantization frequencies depends on what we expect to obtain from the recorded physiological parameter.

Below, as examples which illustrate the method of calculating the capacity of an information source, we will consider the transmission of oscillograms with electrocardiogram, electroencephalogram, electromyogram, pneumogram, and thermogram characteristics through a radio channel. These parameters were selected out of didactic considerations in view of the distinction in frequencies of amplitude and time quantization. We shall consider the transmission of these parameters in the form in which they are recorded by means of contemporary electrographic devices and under the condition of preserving those of their details which are necessary for a

practical evaluation by methods that have obtained sufficiently extensive utilization.

For practical purposes, the spectrum of an EKG recording can be limited to 40-50 cps, which gives a value of n equal to 100. The same number can be obtained by originating from the minimum duration of the QRS complex, i.e., 0.05-0.06 sec, what gives a quantization interval of no more than 0.01 sec. It is more complicated to determine the accuracy of amplitude quantization. It is known that the normal relationship between a maximum R-wave and a minimum P-wave can attain 10:1. This makes it necessary to select at least 20 quantized levels (i.e., an accuracy of 5%). However, when it is necessary to determine the shift of the ST interval by 0.1-0.2 millivolt at an R-wave amplitude (in chest leads) of up to 2.0 millivolts, the number of readings should be increased. For convenience of calculations, we will assume that number m is equal to 16 or 32. This signifies that at any moment of time at the input to the telemetering channel there can appear with equal probability any of the 16 or 32 signals with a fixed amplitude. Thus, by using the Hartley formula we obtain

$$H_1 = n \cdot \log_2 m = 100 \log_2 32 = 10 \cdot 5 = 500 \text{ (When } m = 16, n = 400).$$

Consequently, the capacity of the information source in the electrocardiogram transmission system is equal to 400-500 bits per second.

For analogous calculations in reference to an electroencephalogram, one should consider that a frequency spectrum of up to 100 cps is necessary in clinical practice for manifesting epileptoid spikes. If, however, we base our calculations on the usual methods of visual frequency analysis, a spectrum of up to 40-50 cps will be sufficient. Thus, two values of number n can be obtained — 100 and 200. The accuracy of amplitude quantization, taking into account the amplitude difference of the exalted alpha-rhythm and the low-voltage beta-oscillations, should be no lower than 5% (for convenience, we will assume that n = 16). By the Hartley formula, we obtain:

$$H = 200 \cdot \log_2 16 = 200 \cdot 4 = 800 \text{ bits/sec.}$$

The basic indicators in an electromyogram also are frequency and amplitude. The electromyogram, which represents a curve of non-sinusoidal oscillations, has a frequency spectrum of up to [illegible] cps. This signifies that n should be equal to 1000. With respect to the amplitude characteristics of muscular biopotentials, one should

consider that a diagnostic value is given usually to changes of the order of ±10-20%. Consequently, the capacity of the information source for an electromyographic channel is expressed by a very large number: $H = 1000 \cdot \log_2 8 = 3000$ bits/sec.

The pneumogram is a relatively slow parameter. The respiratory rate in a human, as it is known, attains 50-60 per minute, i.e., does not exceed 1 cps. When recording a pneumogram, the researcher usually is not interested the fine details of the curve. Therefore, the accuracy of amplitude quantization can be selected as 20-25%. Computation by the formula gives a quantity of order of 4 bits/sec. For a pneumographic channel that is intended for investigating animals, in view of the fact that their respiratory rates can attain 200 and more per minute, the amount of information is equal to 16 bits/sec.

$$(H = 8 \cdot \log_2 4 = 8 \cdot 2 = 16)$$

Finally, for transmitting data on body temperature, the telemetering channel should be designed to transmit only about 0.1 bits/sec. Indeed, if we assume a 0.1°C accuracy of temperature measurement on a 20° scale, the number m is equal to 200 (≈256). The discrete nature of the temperature readings cannot be greater than one measurement every few minutes (for instance, 2-3 minutes), i.e.,

$$n = \frac{1}{120} \approx 0{,}01\ (H = 0{,}01 \cdot \log_2 256 = 0{,}01 \cdot 8 = 0{,}08 \approx 0{,}1).$$

Figure 7 represents diagrams of amplitude-time quantization of the indicated physiological parameters which illustrate the discussed calculations.

Total volume of a message (V) to be transmitted through a telemetering channel is determined on the basis of the frequency band (F), the mean signal power (P), and the transmission time (T):

$$V = 2FTP.$$

The quantity 2F is selected in accordance with the Kotel'nikov theorem on the discrete presentation of a signal with a limited spectrum. The quantity P can be defined as $\log_2$ m under the condition of the absence of noise. T is the time in seconds. Thus, it is possible to calculate the volume of a message which contains the recording of any physiological parameter during a specified time interval. For instance, the volume of a message that contains a 30-second electrocardiogram recording is equal to 15,000 bits.

We have considered the question of what amount of information should be transmitted from the information source to the recipient by means of telemetering system, and how much information can proceed to the input of a radio channel per

unit time. However, each channel is designed to transmit a fully specified volume of information. A channel is characterized by its rate of information transmission, its carrying ability, or capacity.

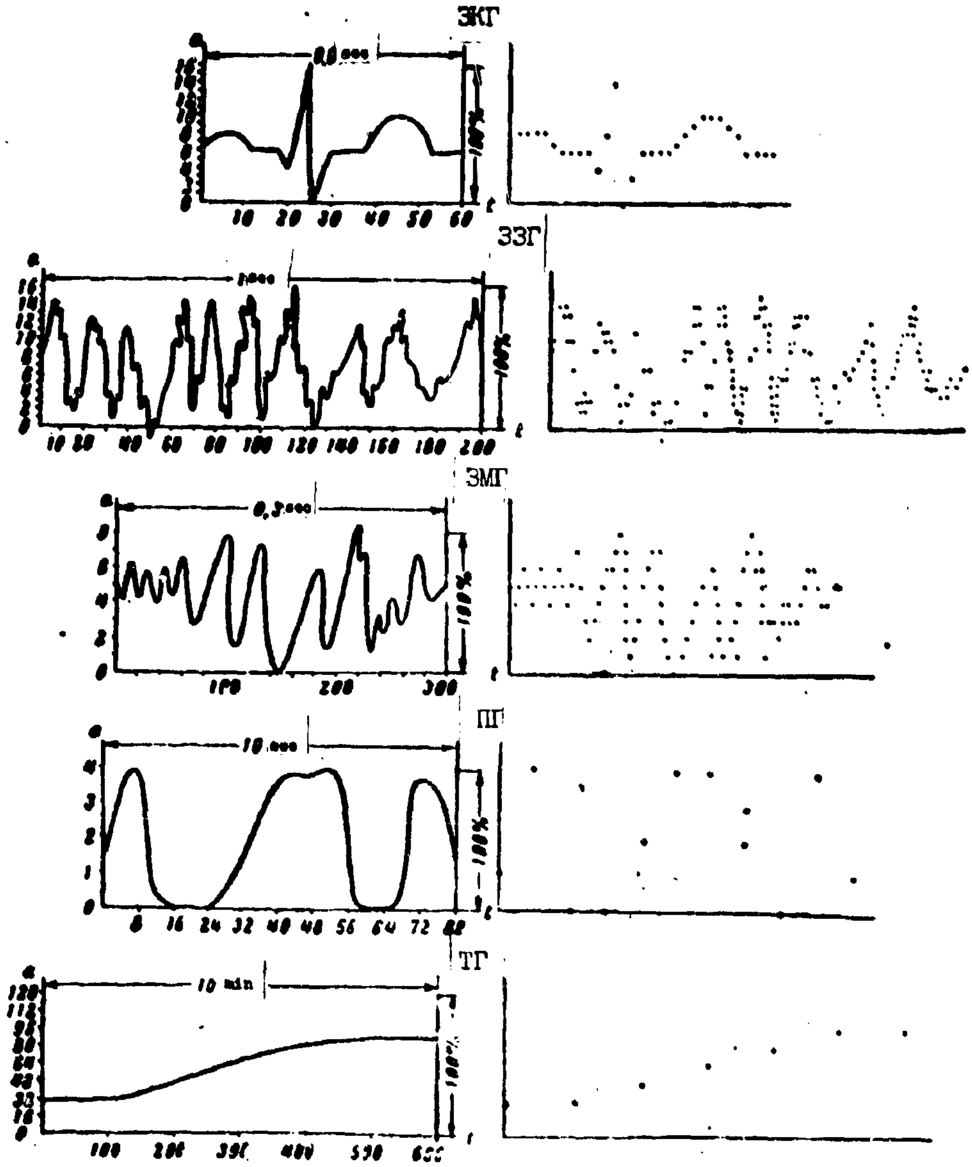

Fig. 7. Selection of optimum frequencies of time and amplitude quantization of an electrocardiogram (ЭКГ) electroencephalogram (ЭЭГ), electromyogram (ЭМГ), pneumogram (ПГ), and thermogram (ТГ).

The capacity of a channel (C) in bits/sec is equal to the amount of information which it can transmit in 1 sec. For an actual channel with noise, there exists the following formula [710]:

$$C = 2F \log_2 \frac{p_c + p_n}{p_n},$$

where p_c and p_n are the signal power and the noise power, respectively. For undistorted transmission of a message, it is necessary that the capacity be a little greater than the rate of information creation by the information source ($C \geq H$). This circumstance must be borne in mind when calculating the capacity of telemetering channels for the transmission of physiological information (Table 3).

Table 3. Tentative Calculations of the Capacity of Sources of Physiological Information and the Capacity of the Telemetering Channels for its Transmission

Physiological parameter	Upper limit of frequency spectrum, cps	Accuracy of level quantization, %	Number of necessary discrete readings		Amount of information, bits/sec	Capacity, bits/sec
			time	amplitude		
Electrocardiogram.	50	5	100	16	400	500 to 600
Electroencephalogram............	100	5	200	16	800	900 to 1000
Electromyogram....	500	20	1000	8	3000	3500 to 4000
Pneumogram........	4	25	8	4	16	20 to 25
Thermogram........	0.005	0.5	0.01	256	0.1	0.1 to 0.2

As can be seen from the table, the transmission of physiological information requires channels with various capacities from 4000 to 0.1 bits/sec. This means that it is either necessary to create special telemetric systems that have channels with different capacities, or, when using standard telemetric systems, to use methods of information storage in the channels. If the volume of a signal exceeds the capacity of the channel, several channels are connected together to transmit one parameter, or the information is converted into a form that is suitable for transmission through a given channel (encoding). All of these methods are known in space biotelemetry.

The telemetric facility used by the American researchers for transmitting biological information from the nose cone of the ballistic rocket "Jupiter" for the monkey launchings in 1958-1959 [481] had channels with different carrying capacities

for transmitting different parameters. The system was based on a combination of the methods of frequency and time multiplexing. Table 4 presents the basic characteristics of this biotelemetric system.

Table 4. Characteristics of the "Jupiter" Biotelemetric System

Parameter	Frequency band, cps	Subcarrier frequency, kc	Number of interrogations per sec	Parameter	Frequency band, cps	Subcarrier frequency, kc	Number of interrogations per sec
Electrocardiogram...	330	22		Rate of pulse wave.	25	1.7	
Pneumogram....	—	30	10	CO_2 content in air.....			
Body Temperature........		30	10			30	10
Temperature of medium....		30	10	Motor responses..		30	10
Cabin pressure		30	10	Stimulant		30	10
				Electromyogram	790	52.5	
Cabin humidity		30	10	Heart tones.	1050	70	

During the flight experiments on the second and third Soviet satellite ships, the method of commutation of 20 slowly varying biological parameters in one standard telemetering channel was used. To do this, the on-board medical equipment included a special mechanical commutator which consecutively connected the information source to the radio channel once every second. The commutated parameters included: body temperature of animals, air temperature and humidity, cabin pressure, and others. In these flight experiments, the volume of signals proceeding through the electromyogram and phonocardiogram recording channels was decrease with the aid of filters in the form of a detector and an integrator with recording of the signal envelope instead of its complete spectrum [11, 29].

In the flight of the "Vostok-5" and the "Vostok-6" the telemetering channel was loaded more fully by the simultaneous transmission of two physiological parameters with different frequency spectra (seismocardiogram and electrooculogram) through one channel.

The problem of optimum loading of telemetering channels takes on an especially urgent value in connection with increasing the duration and range of space flights. The basic task consists of transmitting a maximum amount of physiological information

with the use of the minimum channel capacity. C. Shannon indicates the following three directions of research in decreasing the transmission band of communication channels [710]:

a) using statistical constraints in the message, e.g., optimum encoding methods; b) increasing the signal-to-noise ratio; c) using the information recipient's characteristics.

These directions of research have already been realized to some extent in the field of space biotelemetry. Questions of information encoding will be considered in detail in Chapter 5. In particular, one of the simplest signals, i.e., codes, was transmitted through a "Signal" transmitter during the "Vostok" flights in the form of a sequence of impulses which corresponded to the rhythm of heart contractions. Questions of increasing the signal-to-noise ratio are being solved by the joint efforts of physiologists and medical-equipment designers. The most interestingly trend is the use of the information recipient's characteristics. To illustrate this trend C. Shannon cites an example from the area of verbal communication. He points out that the frequency band for the transmission of speech can be many times narrower as compared to the band necessary for transmitting music in the recipient is interested only in evaluating the semantic value of the messages and is not interested in voice timbre and intonation. This means that the selection of indicators which are of most importance to the recipient, and the sifting out everything which is not essential (for the given concrete case) can serve as an important factor in the creation of narrow-band biotelemetry systems. Investigations in the field of automatic processing of medical information (see Chapter 5) are based precisely on the use of the characteristics of the information recipient, i.e., the physician, who is interested in the fastest obtainment of the results of an investigation without the tedious analysis of initial and intermediate data. The use of a "diagnostic machine" as the information source on board a spaceship, which transmits messages in a code that is optimum for the channel and the recipient, is essentially considered here.

Physiological Measurement and Information Systems in Astronautics

A biotelemetric system which interacts with the subject under investigation, a spaceship, and a ground medical staff is an example of a large class of systems known as information systems [129, 245, 710]. One of the important properties of the objects that make up an information system is their property of containing

information on one another. At the desire of the observer (researcher), from the great number of connections of a specific object with the others, it is possible to isolate only those which are of interest in this case, disregarding the rest. Since we are interested in physiological information, we can consider the system as a physiological one, i.e., having the main purpose of transmitting messages on the physiological state of a living subject. However, this system can differ qualitatively for another observer, such as an engineer. An amplifier design engineer can investigate the noise resistance and noise characteristics of amplifier by using the same information system. The living subject to him in this case will not be the information source, but a generator of test-signals and noises. It is possible to demonstrate that this system can aid in the tasks of studying the operation of telemetering devices, conditions of radio-wave propagation, characteristics of directional reception, and so forth. Moreover, the system can be used for a large number of special measurements which concentrate on the behavior of a living subject; for instance, the operation of a heat-control system may be investigated by means of analyzing the dynamics of physiological functions.

The term "physiological measurement and information system" which we have introduced is intended to reflect the specific nature of the considered system of objects, into which there enter: the information source (human or animal); transducers and electrodes; on-board amplifying equipment; telemetering, transmitting, and receiving devices; devices for recording and presenting data on the ground; the observer (researcher), i.e., the recipient of the information; the spacecraft communications system; the spacecraft television system.

This composition of the information system should also be augmented by all other objects which can change its state by influencing the information source. Such a broad definition of the composition of a physiological measurement and information system makes it possible to consider man in space flight from the point of view of his dialectic unity with his surroundings, i.e., objects, and to consider these objects, in turn, as directly intended for providing the most optimum conditions for the existence of man in space flight. The principle of the system in combination with one clear meaning of its main purpose — to obtain physiological information — makes it possible to purposefully study and plan flight experiments entirely with the use of the large volume of data obtained as a result of each space flight.

Information as one of the properties of matter is a concept which is related to the concept of reflection which is considered by dialectic materialism [245]. The property of reflection consists in the fact that between states of interacting objects there exists a definite conformity; some of them reflect the state of the others. Information theory studies the quantitative side of the states of matter which reflect its various properties. The quantitative approach to physiological information does not simply characterize the state of an object, even in rather clear clinical-physiological terms, but measures this state and expresses it in digital form. The feasibility of quantitative analysis in space biology and medicine can scarcely be exaggerated. This science can be constructed only on the basis of quantitative criteria. In the famous words of D. I. Mendeleyev – "Science begins where measurements begin." It is possible to give many more similar expressions, but, apparently, it is quite clear that the term "measuring" system was not selected at random, but has a profound and important meaning.

Thus, a physiological measurement and information system is a complete set of facilities which make it possible to perform a quantitative appraisal of physiological information. In reference to astronautics, this is the complete set of facilities which provides for obtaining a maximum volume of data about the physiological state of an astronaut.

The physiological measurement and information system of a spaceship is an example of a very complicated (cybernetic) system. This system, in turn, consists of a number of simpler systems and is characterized on the whole by the presence of feedbacks which perform the task of internal control and stabilization. Before we consider the entire system on the whole, let us mention some brief characteristics of its separate elements.

The information source (man or animal) is the basic object of the information system. As we know, the number of various signals which are produced by a living organism is extraordinarily great. According to F. P. Tarasov's classification [245], all signals can be divided into three large groups: 1) communications signals (telephone, telegraph, writing, and so forth); 2) natural signals which characterize the state of an object and, as a rule, are produced by the object itself; 3) measurement signals, where there are two signals – the standard and the one compared with it. In the process of physiological measurements it is necessary to operate with all the indicated types of signals. Communications signals can characterize the activity of an astronaut very well and, when analyzing radio

barriers, his physiological state, emotional stress, and psyche.

Natural signals are all forms of physiological information which are recorded with the aid of various electrodes and sensors. Finally, measurement signals are all stimulus signals, the response to which is a specific reaction that is known beforehand. Here the standard signal is stored in the memory of the information system (for instance, in the memory of the physician who is analyzing the information, or in a table of the results of the preceding experiments). The response of the test subject is the signal which is compared. It is important that neither the standard nor the compared signals themselves carry useful information and that only the total set of these signals gives the measurement information.

It is clear that the number of signals produced by an information source, especially under the complicated and dynamic conditions of space flight, is extraordinarily great. The first and foremost task consists in selecting the necessary signals. Since each already selected signal carries considerably more information than the recipient desires or more than can be transmitted to the ground, the second task consists in removing the surplus of information in the signal in such a conversion of it which makes it possible to transmit the necessary information through channels with the specified carrying capacity (33). We shall further discuss the concept of surplus later. Here it is important to note that a certain surplus of information during transmission is necessary for purposes of counteracting noise and distortions. The simplest example of the creation of surplus is the repetition of a signal.

Signals which are converted and ready for transmission can be either immediately introduced into the communication channel or stored in a memory unit for subsequent transmission, or used for the solution of other problems (signaling, control).

From the above-stated, we can understand the role of the remaining elements of the measurement and information system. The sensors and electrodes select specific information from the huge amount of signals produced by a living organism. The on-board amplifying equipment converts the signal into a form that is suitable for transmission or storage. The telemetering devices (on-board and ground) directly transmit and receive information. The role of the information recipient — the ground medical staff — consists in interpreting the information and processing it into concrete solutions. The realization of these solutions is carried out by the Flight Control Center through command radio lines and radio communications systems. Figure 8 represents a simplified block diagram of a physiological

measurement and information system in reference to the "Vostok" flights.

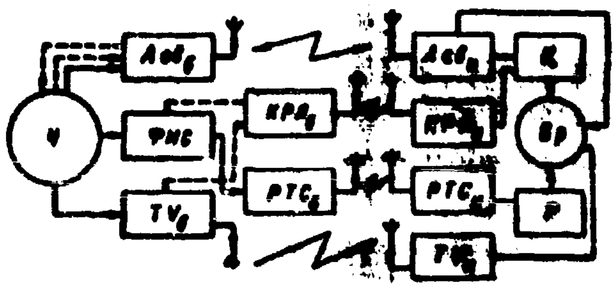

Fig. 8. Block diagram of physiological measurement and information system in reference to the "Vostok" flights.
Ч — man in space flight; ФИС — physiological measurement system of spaceship; TV$_{б}$ — on-board television system; Acв$_{б}$ — on-board communications equipment; PTC$_{б}$ — on-board telemetering systems; КРЛ$_{б}$ — on-board command radio line; Acв$_{н}$; КРЛ$_{н}$; PTC$_{н}$ — corresponding ground systems; P — recorders; B$_{р}$ — physician; Ц — flight control center.

This diagram shows four types of communication between objects of the information system. There are two forms of direct communication, in which natural and communications signals proceed from the information source to the recipient, and two forms of feedback, in which control signals proceed from the recipient to the information source and to the objects of the spaceship. The time of circulation of information in the described system, which used for solving problems of operational medical monitoring in the course of a space flight, is characterized by a specific quantity, i.e., the control signals lag somewhat with respect to the information signals. Thus, one of the indicators of a physiological measurement and information system is the time of circulation of information or the time necessary for processing physiological information into control commands.

Questions of optimizing the circulation of information, and decreasing the lag time of the control signals are considered later and are related to the solution of the problem of automating physiological measurements on a spaceship.

Let us now consider certain practically important parameters of a physiological measurement and information system. The most important requirements of any information system are noise immunity, reliability, and effectiveness [245]. The noise immunity of a system is its ability to transmit information in the presence

of interferences. Measurement of noise immunity can be based on a comparison of the sent and received signals. The greater their difference, the lower the noise immunity. It is necessary to consider that for each system there exist specific accuracies of reproduction. Thus, when transmitting an electrocardiogram, one of the requirements with regard to accuracy consists in generating a P wave which constitutes 0.1 of the amplitude of the R wave. Distortions of physiological information during its transmission to Earth can be caused by different elements of the system. Distortions can be related to incorrect installation of sensors and electrodes. To do this, special research is conducted on the distribution of electrodes and sensors on the human body and animals and on the creation of fixation systems. Distortions can be caused by incorrect selection of the characteristics of the amplifying equipment or by the presence of set noise in the amplifiers. A large class of distortions is related to the transmission and reception of information and to the radio channel; finally, distortions can appear in the process of recording the information. The increase of noise immunity of a system is simultaneously both an engineering and a medical problem. The correct formulation of the requirements for the accuracy of information reproduction, taking into account the carrying capacity of the communication channel, should be based on criteria of radio-electronics technology and information theory to the same extent as on criteria of physiology and medicine.

The reliability of a system is its ability to perform specific functions without failure under certain conditions of operation and time [66, 245, 710]. Reliability refers to probability criteria since it is determined in the form of the probability of failure, which is calculated in reference to a specific period of operation. Since the reliability of a system on the whole depends on the reliability of its separate elements, the reliability of systems decreases as they become more complex. An increase of the reliability of complicated radio-electronic systems pertain to a sphere of two scientific disciplines: radio electronics and information theory. The first is concerned with the problem of increasing the reliability of separate units of the system, i.e., radioelectronic devices, components, and elements. The second investigates the problem of creating sufficiently reliable systems from unreliable elements. There has recently appeared a special discipline, the theory of reliability. The least reliable elements of a physiological measurement and information system are the sensors and electrodes [287]. To obtain high-quality and reliable information, it is necessary

to observe certain conditions with respect to their dimensions, design, and arrangement. Of importance is the proper selection of the physiological parameters for recording under specified conditions. Thus, at present it is practically impossible to create a system which provides for the reliable recording of a human electroencephalogram under conditions of motor activity. Therefore, with regard to the degree of reliability, we can distinguish universal systems, which function reliably under any conditions, e.g., rest, activity, the action of various extreme factors, and specialized systems, which function reliably only under specific given conditions, e.g., under conditions of rest. The reliability of a system should be given in the technical specifications, just as the other parameters.

The reliability requirements are part of the other special requirements for the elements of the system. Thus, when setting up the requirements for an electrocardiogram-recording system, along with the form and dimensions of the electrodes, the method of their fixation, and the quality of the contact paste, the limits of changes of the contact resistance during a specified time also must be given. For instance, a system which varies interelectrode resistance from 5 to 100 kohm in 12 hours cannot be considered to be reliable for a multi-day space flight; however, it is fully reliable for purposes of preflight inspection or for brief laboratory tests.

The concept of the effectiveness of a physiological measurement and information system has two aspects: technical and diagnostic. Technical effectiveness is related to the rate of transmission of the information. Of two systems with identical carrying capacity, the more effective is the one which transmits the specified amount of information in the shortest interval of time [245]. It is clear that an increase of effectiveness is related to a decrease in the surplus of information, i.e., to its optimum encoding [468, 647, 710, 759]. This question is considered in detail later. Here we will mention one of the indicators of technical effectiveness, the information transmission factor, which is defined as the ratio of the ratio of transmission of information through a channel to the rate of creation of information by the source. We already saw that in a number of cases the telemetering channel operates with underloading, i.e., the amount of information transmitted through the channel is considerably below its capabilities. This led to the development of various methods of channel multiplexing: commutation of a large number of slow parameters to one channel and simultaneous transmission of

two parameters through one channel. The complete realization of the capabilities of the telemetering channel is one of the important problems of space physiology.

We have proposed an integral index of the quality of a physiological measurement and informational system. It is called diagnostic effectiveness, inasmuch as diagnostics is essentially the processing of biological information into diagnoses, and then into active measures directed towards the object of measurement (patient). The diagnostic effectiveness of a system can be defined as the ability to solve a specific range of problems with a given volume of transmitted information under given operating conditions. Diagnostic effectiveness in the first place depends on the selection of the parameters subject to registration and on the algorithm for processing the obtained information. Regardless of whether the information is processed by on-board automatic devices or on Earth, or whether medical personnel do it, other things being equal, diagnostic effectiveness to a considerable extent depends on the general level of physiological and medical knowledge and, in particular, on the training of the physiologists and physicians that select the physiological parameters, formulate the requirements for the medical equipment, and develop diagnostic algorithms. It should be noted that with high quality of the electronic equipment and sufficient capacity of the telemetering channels the diagnostic effectiveness can be very low in view of the improper selection of parameters and algorithms for processing the information. Conversely, the well-founded selection of parameters and the application of effective algorithms can ensure high diagnostic effectiveness of the system even when channels with an extremely small carrying capacity are used.

Diagnostic effectiveness is related to the selection of the parameters, the arrangement and design of the sensors, as well as to such indicators of the system as noise immunity, reliability, carrying capacity, and so forth.

In concluding this chapter, let us more clearly differentiate between the two concepts that we have used: the "biotelemetric system" and the "physiological measurement and information system." From our explanations, it is clear that the second concept is more inclusive and broader, and pertains essentially to the field of cybernetics. The "biotelemetric system" to a considerable extent is a technical concept which unites the means for transmitting biological data through a radio channel, and in this sense constitutes one of the elements of the physiological measurement and information system. The biotelemetric system, just as the physiological measurement and information system, is a particular case of a

particular case of a "biological measurement and information system."

CHAPTER 3

CONTEMPORARY PHYSIOLOGICAL MEASUREMENT SYSTEMS ON SPACECRAFT

Flight experiments with animals and manned space flights made it possible to gain a great deal of experience in constructing physiological measurement systems for providing flight safety and solving research problems. This chapter considers the various aspects of contemporary physiological measurements in space: problems of information collection, features of the on-board radio-electronic equipment, questions of transmitting and recording data, and also the features of setting up a flight experiment and evaluating it. Prime attention is given here to the medical side of the considered problems, although in certain cases it is also necessary to concern outselves with technical questions. This once again emphasizes the important role of creative collaboration of physicians and engineers in providing for physiological measurements in space flight.

Transducers and Electrodes

In order to select the necessary physiologic data from the huge volume of the various signals produced by the information source, transducers and electrodes are the elements of a physiological measurement and information system which coordinate the information source with the on-board physiological radio-electronic equipment. A transducer is a device which is activated by the energy of one system and produces energy for another system, or a device which converts one form of energy into another form, or a device which receives specific information and returns it in a specified form. There are other definitions of the term "transducer," whose abundance indicates the attention which is given to this device in the various fields of science and technology. The problem of transducers occupies a special place in medical electronics

in view of the fact that progress in the field of transducers essentially determines the achievements in the field of methodology. The development of each new research method in physiology usually begins with the creation of an appropriate transducer. In general, the use of electronic technology and equipment in medicine to a considerable extent involves the conversion of nonelectrical (biological, physiological) quantities into electrical quantities [22, [illegible], 318, 205, 194, 735].

Certain biological processes have an electrical nature or are accompanied by changes of electrical potentials in tissues. Electrodes are used to investigate these processes. An electrode is a device which is intended for contact reception of the electrical potentials that appear in a living organism. There are the following types of electrodes: surface, inserted (needle), implanted, and intracavitary.

In space physiology, surface (for humans) and implanted (for animals) electrodes are used to obtain information in a flight experiment.

Transducers and electrodes play an important role in ensuring of high noise immunity, reliability, and effectiveness of the physiological measurement and information system of a spaceship. Any, even the most effective, physiological method can be useless if effective information collection is not ensured with the aid of perfected transducers and electrodes. The uniqueness and high cost of a flight experiment imposes requirements of high reliability on the whole physiological measurement system. We know of cases when the malfunctioning of a transducer and reak in the wire have essentially decreased the volume information obtained in ight [449, 481]. In the multi-day space flights of the "Vostoks" the EKG electrodes were duplicated, which sharply increased the reliability of the measurement system [10].

According to their principle of action, all transducers can be divided into two categories: generating and parametric. The first ones produce electrical signals themselves, which are equivalent (isomorphic) to the investigated biological process. The second ones change their electrical characteristics (parameters) in accordance with the dynamics of the biological process. Transducers of the generating type are more preferable in space investigations since they do not require special measurement systems and power sources.

R. Stacy [735] proposes to place transducers in the category of primary converters if the electrical signal appears in them as a result of the direct influence of an observable phenomenon (microphones for recording of heart tones, potentiometers for recording movements); transducers belong to the category of secondary converters if there are any intermediate devices for transmitting the process under investigation

to the transducer's sensor. As examples of secondary converters we can mention the electrodynamometer, in which straining of the steel springs causes the potentiometer slider to move and the anemometric respiratory transducer, in which a stream of exhaled air revolves a light miniature turbine whose blades cause oscillations of the beam of light which strikes the photocell, or the excitation of induction currents in a coil because of the motion of miniature magnetic elements. It is clear that secondary converters which have intermediate devices possess poorer characteristics than primary ones. In addition, their size and weight specifications are also less applicable. Therefore, in space investigations it is expedient to employ chiefly primary converters.

Also of interest to space physiology is the classification of transducers according to their power interrelationships with the object of measurement. We developed this classification on the basis of an analogy with the classification of biocybernetic automatic devices [196]. We propose to distinguish biocontrolled transducers and power transducers. Biocontrolled transducers include all generating transducers and most parametric transducers. These are the transducers which produce signals by using the information from the biological subject under investigation as a control. The process of biological control essentially is accomplished in miniature here; the subject controls the transducers operation by making it generate electrical signals or change its electrical parameters. Power transducers operate on the principle of recording the effects which appear as a result of the influence of some form of energy on the investigated subject. A classic example of this type of transducer is the pickup unit of an electrokymograph. Here, changes in intensity of X-radiation passing through the section of tissue under investigation are converted into oscillations of electrical current. The same type includes transducers of instruments for rheography, oxyhemography, and ultrasonic location. The value of the described classification of transducers in astronautics lies in the fact that in a prolonged investigation it is not possible to use power transducers since, on the one hand, it will demand additional power consumption for constant action on the organism and on the other hand, prolonged action can render an unfavorable influence, especially in the complicated and, in many respects, vague conditions of space flight. Therefore we consider, for example, the use of the method of impedance pneumography in prolonged flights which the American researchers employed during the flights W. Schirra and G. Cooper to be inexpedient [788, 790]. Of course, this does not mean that power transducers cannot be used for brief research recordings.

Thus, the methods of oxyhemography (152) and rheography (135) should find their application in future research equipment on spaceships.

Later we shall consider general questions of the design and application of transducers and electrodes in space physiology. We shall turn our attention to the fundamental principles of operation of various types of transducers, the methods of investigating their operating characteristics, and the problems of connecting the transducers to the on-board radio-electronic equipment. A detailed description of special transducers which have been used in Soviet space research will be given together with an account of the corresponding methods of physiological research.

The development of transducers and electrodes for application under conditions of space flight has its difficulties [80, 598, 458, 779]. The necessity of their prolonged and continuous operation while maintaining their operating characteristics constant during and after the action of various factors (vibrations) accelerations, various atmospheric factors: (temperature, humidity, barometric pressure), and also the impossibility of replacing them in case of failure during flight forces us to seek newer methods of recording physiological reactions and to design more improved types of electrodes and transducers. A serious problem is the arrangement of electrodes and transducers on the bodies of astronauts. On the ground, the inconveniences experienced by a man during certain investigations are very brief; in flight, they become constantly acting factors. Transducers and electrodes should not interfere with the work of an astronaut or cause him any discomfort. This statement equally pertains to animals inasmuch as symptoms of discomfort cause them to be restless, and increase their motor activity, which cannot fail to show up in the results of the physiological investigations.

The arrangement of transducers and electrodes on the subject to be investigated (man or animal) is quite difficult. Most transducers and electrodes must be placed at specific points, and a small displacement of them to the side may cause essential distortion of the recording. In investigations on animals, the escape from this difficult situation was found by means of implanting electrodes under the skin or in a muscle, with the application of special operative methods which ensure exact fixation of the transducer (for instance, drawing out the carotid in dogs into a skin flap for measuring arterial pressure and sphygmogram recording, [82]. Methods of implanting transducers in the thoracic [421] and cranial [179, 180] cavities have been described. The task of arrangement and fixation of transducers and electrodes on the human body is significantly more complicated. At present there exist many proposals for gluing electrodes and transducers to the skin, sewing them into clothes,

placing them in natural orifices (rectum, nose, oral cavity), and even implanting them under the skin. The most expedient turned out to be a system of attachment with the application of special chest belts and helmets, as was done in the flights of A. G. Nikolayev, P. R. Popovich, V. F. Bykovskiy, and V. V. Tereshkova [10, 11, 294, 295].

For application in space investigations, the transducers of physiological measurement systems must possess a large number of qualities. They have to be as small as possible, constructively convenient for arrangement and fixation, must not have sharp and protruding edges, must not contain liquid and semiliquid elements (oil, alcohol), must not consume energy as much as possible, and must not render an energetic influence on the subject of investigation. Of importance is the method of connecting the transducer to the amplifying equipment. To provide for sustained measurements, the contact heads of the transducer are connected to a system of lead-off wires by means of soldering. Miniature built-in plugs are used for periodic-action transducers. Transmitter pickups have recently started to be developed. They are miniature devices which contain their own transducers and amplifiers, and a transmitter which relays data to shore distances within the cabin of the spaceship [27, 40, 192, 579].

The basic operating characteristics of transducers which are of interest to the physiologist are sensitivity, working range, frequency-response curve (inertness), and linearity. The sensitivity of a transducer can be defined as the magnitude of the output signal per unit of the input signal. Thus, if the output signal is voltage, and the input signal is the mechanical movement of a vascular wall (piezoelectric transducer for sphygmogram recording), the sensitivity may be expressed in microvolts per micron of displacement, bearing in mind that the displacements of a vascular wall can attain 100 and more microns. The sensitivity of a similar transducer with a tensometeric converter can be expressed in fractions of an ohm per micron of displacement or in microamperes (current in the circuit of a measuring bridge) per micron of displacement. In space investigations, sensitivity is usually calculated in reference to the entire physiological measurement and information system. Thus, when measuring the body temperature of the animals during the flight of the second and third Soviet satellite ships, the values of temperature were computed directly in percents of the scale of the visual indicator of the ground telemetric station, whereupon 100% corresponded to a change in temperature from 30 to 40°, i.e., 1°C = 10% of the scale. In the given case we encounter two other characteristics of a transducer, i.e., working range and linearity.

For a thermistor transducer, the specific range of resistances corresponds to a temperature range from 30 to 40°C. The transducer should be designed in such a way that the range of the working values of its resistance corresponds to the given range of changes. For a transducer that is intended for measuring the displacement of a vascular wall, the working range of sensitivity should be selected within the limits of 10-100 microns.

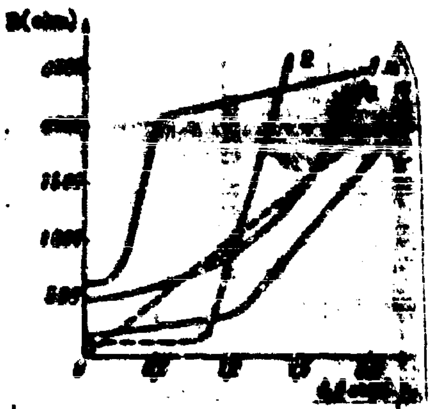

Fig. 9. Operating characteristics of various active resistance transducers. 1 (a, b, c) — carbon transducers; 2 — potentiometer pickup; 3 — contact-potentiometer pickup.

An important advantage of a transducer is the linearity of its operating characteristic, i.e., the changes in the output signal linearly correspond to the changes in the input signal. This characteristic is depicted by a straight line on a graph (Fig. 9). Transducers with linear characteristics create definite conveniences during subsequent analysis of experimental data. Linearity is especially important for transducers which operate in operational monitoring channels, where the rate of information analysis has a decisive value. It should be noted, however, that the application of automation for processing physiological information makes the problem of linearity less urgent.

The frequency-response curve of a transducer is the range of frequencies that can be reproduced by the transducer without distortions. The frequency-response curve of a transducer should correspond to the frequency range of the input signal. The input signal can be subject to integration or differentiation in the transducer itself if its frequency-response curve shifts in the direction of low or high frequencies as compared to the frequency of the input signals. Thus, in pulse recording with an electromagnetic (induction) transducer, there usually is obtained a differential curve (speed recording). This is related to the fact that electromagnetic transducers usually have very low sensitivity at frequencies up to 20 cps, and their frequency-response characteristics lie within the limits of 50-500 cps, while the frequency range of pulse fluctuation is from 0.1 to 40 cps. Conversely, potentiometer transducers have a frequency-response characteristic from 0 to 20-30 cps, and their use, even for recording such a relatively low-frequency process as respiration, leads to the obtainment of integrated curves. Thus, the selection of the type of transducer and the development of its design are directly related to problems of physiological measuring and should be solved jointly by the physiologist

and the engineer.

Active Resistance Transducers

Active resistance transducers or ohmic transducers change their electrical resistance as the measured quantity changes. Their simplest form is the potentiometer transducer. It consists of a wire-wound resistor, along which there moves a slide contact. It is essentially a potentiometer which is connected to the object of measurement. Similar transducers were used during experiments with animals for studying their motor activity and spatial position. The animal is connected to a potentiometer movement pickup by means of a Kapron cord which is attached to fixing "clothes." The resistance of the potentiometer is directly proportional to the length of the cord (see Fig. 9). The direct component of output voltage indicates the animal's position inside the capsule with respect to the point of attachment of the transducer (the distance from this point). The alternating component makes it possible to estimate the degree of motor activity and also to see what the animal is doing precisely (Fig. 10).

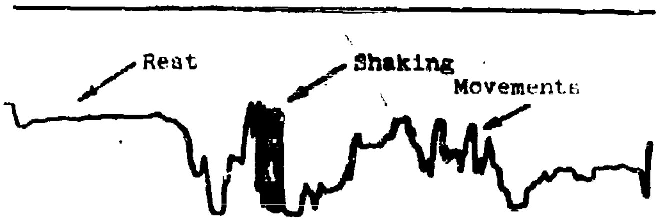

Fig. 10. Animal movements recorded by a potentiometer pickup.

Another type of active resistance transducer that was developed for recording movements is called the contact-rheostat transducer. The magnitude of resistance of this transducer depends on the force applied to the cord which connects its cursor to the object of measurement. The measurement system is turned on only during the action of a specific force, i.e., the contact system signals the minimum efforts of the animal.

Potentiometer pickups in the form of an elastic rubber tube filled with carbon powder have received much use because of their simplicity [518]. This type of transducer is placed above the elastic insert of the chest harness and changes its length in accordance with the change of the perimeter of the chest (Fig. 11). The peculiarity of the carbon transducer consists in its nonlinearity. Figure 9 shows the typical characteristic curve of this type of transducer (the relation of resistance to length). The same figure illustrates the characteristics of potentiometer and contact-resistance movement transducers. As can be seen, the carbon transducer can have a rectilinear section of its operating characteristic, in which

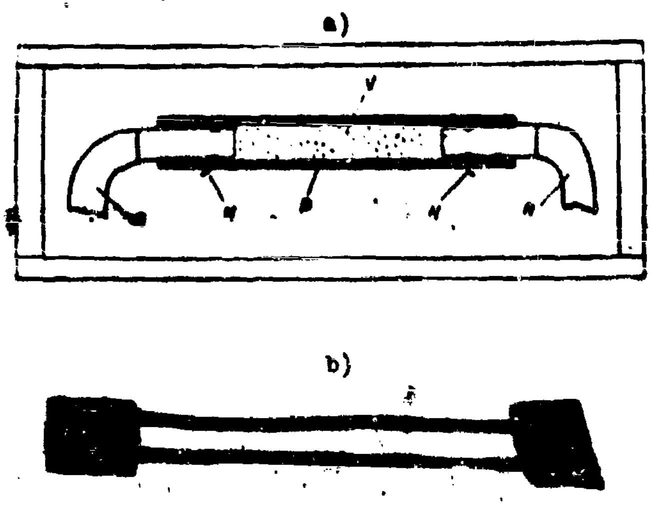

Fig. 11. Carbon transducer for pneumogram recording. a — drawing of carbon transducer; P — rubber tube; У — carbon powder; П — wire; H — filament which secures lead-off wires; b — external view of transducer.

resistance is directly proportional to length. The working range of the transducer when it is installed is selected within the limits of the rectilinear section, where it usually possesses the greatest sensitivity.

Variations of the carbon transducer are the electrolytic and mercury transducers [318, 736]. In this case the rubber tube is filled with an electrolyte solution or mercury, respectively. The advantage of these transducers is good linearity in a wide range of values; their disadvantage is the difficulty of making them airtight. In one of the first American ballistic flights under project "Mercury," a respiration transducer filled with a solution of copper sulfate was tested [789].

Another variation of the carbon transducer are the tensolite elements for sphygmorgram recording [30] and pneumoelectric converters with the use of a carbon crophone [223].

Active resistance transducers include thermistors. A thermistor is a resistance thermometer made from semiconductor material with a high temperature coefficient. Thermistor transducers have been employed for monitoring the temperature regime of spaceships, including air temperature, and also for temperature changes in animals and humans. The application of thermistors was conditioned by their high sensitivity (approximately 10-15 times greater than the sensitivity of copper resistance thermometers) and small dimensions which make it possible to create transducers that can be placed at any point of the body.

Thermistor transducers are applied not only for measuring body temperature, but also for recording oscillations of air flow [15, 670]. For instance, thermistor transducers were widely used in American space research for recording the respiration of animals [523, 650].

In this case a current is sent through the thermistor with such a magnitude so as to ensure its heating to a temperature of about 200°C. The thermistor is placed in the path of the air flow and the fluctuations in air speed change the temperature

of the thermistor. The voltage drop in it can reach 30-60 millivolts. These voltages are proportional to the speed of the air flow which cools the transducer. Vibrations and accelerations practically have no effect on this type of transducer. Similar transducers have been called thermoanemometric transducers. They are used for recording pulmonary ventilation, pulse oscillations of air flow during the measurement of arterial pressure (pneumooscillograms), and in other cases. Active resistance transducers also include etric transducers, which have be employed a great in medicine and physiolo].

Piezoelectric Transducers

In piezoelectric transducers, the conversion of nonelectric (mechanical) quantities into electrical ones is based on the appearance of electrical charges on the faces of certain natural or artificially created crystals when they are strained by external forces. The charge that appears due to the piezoelectric effect is directly proportional to the strain. The change of the magnitude of the charge depends on the rate of change of the magnitude of mechanical stress (strain):

$$\frac{dq}{dt} = Rn\frac{d\sigma}{dt},$$

where q is the density of the charge (in coul/cm^2), Rn is the piezoelectric modulus (in coul/kg), and σ is the stress (in kg/cm^2).

The piezoelectric modulus for quartz has a magnitude of the order of $2\cdot10^{-11}$, and $2\cdot10^{-9}$ for barium titanate. Piezoelectric transducers belong to the generating-transducer class.

When building transducers that are based on the piezoelectric effect, it is necessary to consider that they are recording the first derivative of a controlled process, i.e., charges exist on the piezoelectric element as long as there is strain. So that the leakage of charges least distorts the results of the investigation, it is necessary that the time constant of the transducer be sufficiently great as compared to the period of measurement of the controlled quantity. The time constant of a transducer is computed by the following formula:

$$T = \frac{C + C_{ex}}{G + G_{ex}},$$

where C and C_{ex} are the capacitances of the transducer and the input circuit of the electrical network, respectively; G and G_{ex} are the conductances of the transducer and the input circuit of the electrical network, respectively.

When recording physiological processes with the aid of piezoelectric transducers there usually occurs differentiation of the measured stress. This must be considered

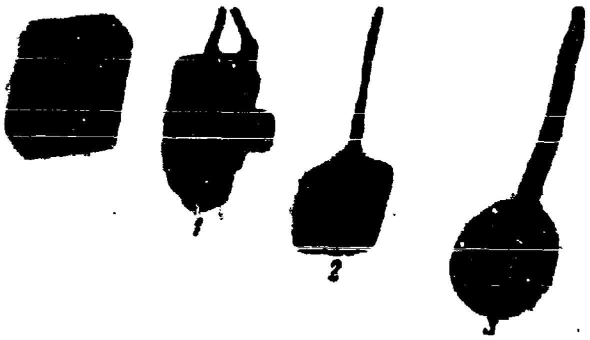

Fig. 12. Samples of transducers for kinetocardiogram recording. 1 — transducer with rectangular piezoelectric element and pellet; 2 — transducer with piezoceramic disk; 3 — electromagnetic transducer.

when decoding and analyzing the data. Piezoelectric transducers were used on Soviet spaceships and artificial earth satellites for recording arterial oscillations when measuring arterial pressure and for recording sphygmograms of the carotid in animals. United States made attempts to use piezoelectric transducers for recording heart tones.

We have developed high-quality transducers for recording the vibrations of the chest wall (kinetocardiograms). They serve as the prototype of the electromagnetic kinetocardiographic transducer that was used on the "Vostok-2" [8, 10]. Samples of piezoelectric transducers are shown in Fig. 12; the same figure illustrates an electromagnetic transducer similar to the one which was used in G. S. Titov's flight. The difficulty of applying piezoelectric elements in transistor circuits lies in the fact that a piezoelectric transducer requires a high input amplifier impedance, and this is very complicated to ensure in transistor devices.

Induction Transducers

Induction transducers are based on the phenomenon of electrical induction. n the magnetic flux in a conductor is changed, an electromotive force (e), is induced, the magnitude of which is determined by the following formula:

$$e = B \cdot l \cdot v \cdot \sin\alpha,$$

where B is the magnetic flux in oersteds, l is the number of turns of the induction coil, v is the speed of the magnet, α is the angle between directions of coil turns and magnetic lines of force.

There are two types of induction transducers: those with a moving magnetic field and those with a varying magnetic flux.

An example of the first type is the seismocardiographic transducer that is intended for investigating the mechanical efforts of cardiac activity. It has a moving magnet which performs the role of a seismic mass and is connected to the transducer housing by a steel spring. The vibrations of the body which are caused by cardiac activity produce oscillations of the seismic mass (magnet) and movement of the magnetic flux relative to the stationary coil. A detailed description of various types of seismo-transducers is given in Chapter 5.

For recording acoustical phenomena of cardiac activity and local vibrations of the chest wall, induction transducers are used with a varying magnetic flux which are constructively similar to electromagnetic telephones. This type of transducer (see Fig. 15) is a small induction coil placed in an ebonite case, with a core made from a magnetic alloy and a diaphragm that influences the amount of magnetic flux in the coil. Similar transducers were used for recording heart tones (phonocardiogram) and for recording vibrations of the chest wall (kinetocardiogram). The frequency response of electromagnetic transducers is in the range of 50-500 cps. Therefore, low-frequency vibrations are recorded in the form of speed curves. Rosa and Luisada [684] conducted special research in the question of the character of oscillograms of cardiac vibrations obtained by transducers with various frequency responses. It was shown that the electromagnetic transducers, as compared to the capacitance and piezoelectric transducer, other things being equal, gives a speed or acceleration curve (Fig. 13). The speed character of the curve is determined by the principle of action of the induction transducer itself, since the electromotive forces are functions of the magnetic flux, number of turns, and time. The sensitivity of the transducer is higher, the greater the number of turns in the induction coils and the higher the magnetic properties of the core. Electromagnetic transducers possess good linearity within the operating range of frequencies and with small displacements (to 100 microns).

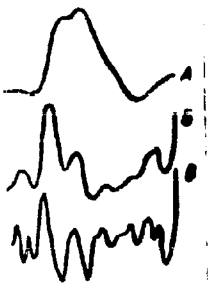

Fig. 13. Displacement (A), speed (B) and acceleration (B) curves when recording vibrations of the chest wall with various transducers (Rosa and Luisada, 1959).

Other Types of Transducers

Among the numerous methods of converting nonelectrical quantities in electrical ones, we shall mention those which have obtained rather extensive application in various medical instruments or are perspective in the sense of their use on a spacecraft.

Photoelectric transducers are usually designed on the basis of photoresistors (photocells with photoconductive effect). A change in the intensity of light which strikes a conducting layer causes a change of the current in an electrical circuit. Sensitive plethysmographic transducers, transducers for recording ballistocardiograms, internal pressure, and respiration were developed. Oxyhemograph transducers also are photoelectric.

Capacitor pickups have been employed in generator circuits, where they are

resonant circuit elements. These transducers, just as the photoelectric ones, record movements. Recently Ye. K. Luk'yanov, I. I. Samorukov, and others developed original and very sensitive capacitor pickups for investigations of pulse and respiration [163]. Capacitor pickups are used in plethysmography. The principle of the change in circuit capacitance is the basis of the dielectrocardiographic method.

Electrochemical transducers use various electrochemical reactions. In particular, electro-osmosis transducers based on the u-effect have been employed the appearance of electrical potentials on the boundary of two liquids with different surface tension). These transducers are sensitive to accelerations.

Mechanotron transducers are miniature electron tubes with movable anodes. Micro-displacements of the anode cause changes in the anode current. The parameters of the electron tube are thus controlled. Transducers for measuring arterial pressure pulse, motor activity, and other physiological parameters were designed on the basis of mechanotrons.

Electrodes

A significant group of physiological measurements is performed strictly speaking, without transducers — the investigation of the electrical processes of a living organism.

Surface or inserted electrodes are employed for recording biopotentials in space physiology.

Electrodes are unique "transducers" of measurement systems. Bioelectric measurements involve the necessity of providing reliable electrical contact of the electrode with the investigated living tissue. This is very complicates task since it is not a question of several minutes, as under laboratory or clinical conditions, but of hours and days. The fact is that a change in the "electrode-tissue" transition resistance creates distortions and interference, and frequently makes investigation impossible. Of large value is the correct location of electrodes in accordance with the laws of distribution of an electrical field in the volume of a conducting substance, i.e., tissue. It is assumed that the medium surrounding the source of electrical potentials is uniform in an ideal case. The magnitude of the potential of fixed points on the body surface is inversely proportional to the square of the distance from the investigated organ or tissue and depends on the location of the electrodes. Under actual conditions, electrical nonuniformity of body tissue disturbs theoretical calculations and requires appropriate experimental investigations. In practical electrophysiological measurements, the biopotentials

are tapped with the aid of two electrodes which can be arranged in monopolar or bipolar fashion. The monopolar electrode position signifies that one electrode is in the section of the body where the investigated potential is extremely small or approaches zero. The second electrode, which is then located near the biopotential source with respect to the "zero" electrode, measures the "true" value of the biopotential at a given point. In the biopolar arrangement, both electrodes are above the organ or tissue which possesses bioelectric activity. The absolute value of the biopotentials is not measured here, but the difference value. In the case of bipolar leads, it is necessary to use a third "zero" electrode, which ensures the operation of the noise-suppression system in the amplifier (see below).

When recording biopotentials, special attention must be given to the inter-electrode resistance, selection of points for locating the electrodes, their fixation and noise elimination. For electrodes which are inserted into animal tissue, it is extremely essential to select an appropriate material which would not cause a biological response from the surrounding tissues and would not traumatize them. The amplitude of the biopotentials varies from several microvolts (brain potentials) to several millivolts (galvanic skin potentials); the frequency range of bioelectric phenomena lies from zero to a thousand cycles per second. Thus, when recording biopotentials, the researcher must solve a large number of diverse questions of both a medical and an engineering nature.

The important role of electrodes in space research is stipulated by the fact that the most popular and universal method for medical monitoring and investigations is electrocardiography. In spite of its substantial age (over 50 years old), this method essentially had to be specially modernized for application in space research. A significant portion of this work consisted in research on seeking methods of reliable and long-term tapping of biopotentials.

On-Board Radioelectronic Physiological Equipment

An important element of the physiological measurement system on a spaceship is the on-board radioelectronic equipment. Its role consists in converting signals from transducers and electrodes into a form suitable for introduction into the telemetering device. In the process of information conversion, the information is amplified, its spectrum is limited, and it is integrated or differentiated. The on-board equipment provides the final coordination of the capacity of the information source with the carrying capacity of the radio channel. The equipment for recording physiological information that is placed on board a spaceship has a number of essential distinctions

as compared to ground instruments. These distinctions are related, on the one hand, to weight and size limitations, and the expenditure of electric power, and on the other hand, to the specific operating conditions of the equipment [159, 367, 428, 526, 665, 649, 732, 800]. As a rule, to provide for each new series of flight experiments, new types of on-board equipment are developed which correspond to the specific tasks of the experiment and the design of the spacecraft. The formulation of the medical-technical specifications (MTT) for this equipment is the first stage of its development and is carried out jointly by engineers and physiologists. The MTT must consider: a) the program of future experimentation; b) the possibility of recording one parameter or another under flight conditions; c) the possibility of transmitting the measured parameters to the ground; d) design limitations (weight, dimensions, power consumption); e) the operating conditions of the equipment.

It is natural that when the MTT are set up the level of development of medical electronics is taken into account in order to use all the latest achievements in this field to the fullest extent.

Samples of on-board equipment are developed in reference to specific flight experiments and specific spacecraft. Therefore, the equipment's makeup is determined by the program of futures biomedical research.

In one series of flight experiments, if necessary, according to the results of the preceding flight, the telemetry program of the next flight can be modified. However, in view of the spacecraft equipment of the given series, the apparatus can be made of the same type only by modifying the transducers and electrodes in reference to the already existing amplifying and measuring channels. There is experience in this type of telemetry program correction. Thus, for instance, in the flight of the third Soviet satellite ship with the dogs Pchelka and Mushka, one of the EKG channels was used for recording mechanical activity of the heart with the aid of a seismotransducer, while the electromyographic channel was used for phonocardiography.

In the flight of the "Vostok-3" and the "Vostok-4," preamplifiers which operated jointly with the EKG channels were used for electrooculogram and electroencephalogram recording.

Since the information source must be coordinated with the amplifying and measuring channels of the on-board equipment by means of transducers and electrodes, the latter also must be coordinated with the parameters of the telemetering system. If the resolving power of the telemetry provides for the transmission of a frequency band from 0 to 50 cps, it is senseless to design amplifiers with a frequency band to

500 cps, e.g., for electromyography.

If the radio system permits the transmission of 1 signal per second, for instance, none of the physiological parameters such as the electrocardiogram, pneumogram, or electroencephalogram can be transmitted without special treatment. Thus, when setting up the medical-technical specifications for the on-board physiological equipment, the characteristics of the input information and the telemetric devices must be taken into account.

Frequently, however, for the purpose of more economic use of the telemetry lines, engineers and physiologists agree on compromised solutions when the amplifying and measuring channel is designed in such a way as to transmit a specific portion of physiological information to Earth. For instance, on the third Soviet satellite ship, the electromyogram was recorded by means of an amplifier with a detector at its output, which ensured the transmission of data only on the amplitude of muscle biocurrents, which means that it permitted the use of a telemetry channel with a capacity 10 times less than that required for transmitting a natural electromyogram. Of course, the information on the frequency spectrum of the biopotentials was lost in the detector curve. However, the amplitude characteristics of the electromyogram obtained under conditions of G-loads and weightlessness were of much interest to the physiologists.

Of importance is the amplifcation factor of the channel. The information that proceeds from the transducers and electrodes has a variable intensity (with respect to voltage — from one microvolt to ten millivolts). For introduction into the telemetric system, signals are necessary which vary in magnitude in the standard range, for instance from 0 to 5 v [662]. Therefore the amplifying and measuring channels must possess different amplification factors depending upon the voltages produced by the transducers.

We should point out one of the most important features of amplifiers which are intended for recording biopotentials, i.e., the necessity of measures for noise suppression. The object of investigation always is in some sort of an electrical field which is caused by the operation of various electrical instruments and the electromagnetic radiation of the wiring in the a-c network. A noise voltage is formed at the input terminals of the amplifier due to the capacitive coupling with the external source of electric power. Under laboratory conditions, the application of shielded chambers can completely exclude noise. In flight, if a man or animal is placed in a cabin which is a shielded chamber and there are no sources of interference such as an a-c network, conventional amplifier circuits can be used without

shielding. Thus, during flight experiments with animals, the so-called asymmetric amplifier circuits, which have an identical amplification factor both for the useful signal and also for cophasal interference, were successfully used. However, in the preparation for a manned space flight, the application of similar amplifiers turned out to be impossible since the astronaut was not shielded from sources of electromagnetic radiation of the craft's equipment, and also because on all stages of checking and complete testing of the on-board equipment, which are conducted under plant conditions or at the launch site, he is in the sphere of action of strong electrical interferences.

All this leads to the necessity of developing amplifiers which are not sensitive to noise signals, especially those related to an a-c network. Similar amplifiers are the so-called differential amplifiers. Their main property is that amplification of the signal that goes to both input wires in one phase (cophasal) is relatively small with respect to the grounded point. The useful signal from the electrodes is inserted between the tube grids (or triode bases) and is amplified many times stronger than the noise signal. The relationship between the magnitudes of amplification of the useful signal and the noise signal is called the discrimination factor and serves as a criterion of amplifier quality in the sense of its noise immunity. The smaller the magnitude of the useful signal, the higher the discrimination factor the amplifier must have. Amplifiers that are placed on spacecraft must have the following discrimination factors: 1:500 for heat biopotential amplification and 1:5000 for brain biopotential amplification.

The amplifying and measuring channel, besides the corresponding characteristics with respect to amplification, frequency range, and discrimination factor, should ensure a specific accuracy of measurements. By accuracy of measurements we mean the highest permissible magnitude of the basic error expressed in percents of the upper limit of the measurements. Nonstandard operating conditions of the equipment (electrical interferences, changes in temperature and humidity, changes in supply voltages) may cause additional errors. Thus, when recording an EKG under conditions of the influence of strong electrical interferences, it is difficult to accurately measure the amplitude of its individual waves. Systems for measuring temperature or resistances change their accuracy under various influences, such as a considerable increase in humidity or temperature.

For quantitative measurement of physiological information, a control (standard) signal is sent to the input of the amplifying and measuring channel. It is usually a square pulse with a definite, strictly specified value. A 100-microvolt control

signal is employed to calibrate the electroencephalographic and electromyographic channels, and a 1-millivolt signal for the EKG channels. In the on-board physiological equipment on the second and third Soviet satellite ships the control signals were sinusoidal voltages of 15 cps-1 mv for the EKG channel and 400 cps-100 μv for the electromyographic channel.

A distinctive feature of the on-board physiological equipment is automatic control from a program device or by signals sent from Earth through a command radio link (КРЛ) [CRL]. Connection and disconnection of the equipment is strictly synchronized with the beginning and end of the period of telemetric communication. This ensures an economical power consumption by the supply sources. The reliability of the amplifying channels is increased by supplying them from separate voltage converters. These converters ensure the obtainment of various voltages from the on-board source and stabilize them. In the event of a breakdown of one of the converters, the remaining channels retain their efficiency.

The on-board equipment in the first Soviet space experiments was designed with the use of miniature bantam tubes. The "Vostok" and "Voskhod" crafts employed equipment which was completely transistorized. Some brief information is given below on the on-board radioelectronic physiological equipment applied in Soviet and American space experiments.

Second Soviet Artificial Earth Satellite

The biological experiment on the second Soviet artificial earth satellite was an extremely important stage in the development of space medicine and biology. To record the physiological functions of the dog Laika, a special set of medical equipment was designed which provided for electrocardiogram, pneumogram, arterial pressure, and motion recording [56].

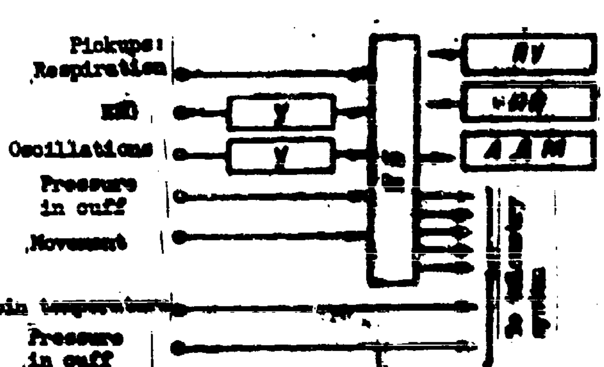

Fig. 14. Block diagram of on-board physiological equipment of 2nd artificial earth satellite. У – amplifiers; КБ – switching block; ПУ – control panel; ВП – power supply; АДМ – automatic pressure control in cuff.

The equipment included pickups, two amplifiers, a switching block, an automatic pressure control device, and a program device (Fig. 14). One of the amplifiers was used to record heart biopotentials and second was for recording oscillations of the carotid walls of the animal. The pressure in a

cuff which was placed around an artery was created with the aid of the automatic pressure control device. The oscillations in the cuff were recorded with the aid of a piezoelectric pickup. The movement pickup was of the potentiometer type and the respiration pickup was of the rheostat type.

The equipment also provided for the recording of air pressure and temperature in the cabin.

The program device periodically turned the equipment on and off in accordance with the periods of telemetric communication.

Second and Third Soviet Orbital Spacecraft

The second and third Soviet orbital spacecraft are frequently called "flying space laboratories." Indeed, with respect to the volume of physiological information obtained in these flights, they are unexcelled examples of scientific experimentation in space. An important role was played by the on-board radioelectronic medical equipment. In the accordance with program of investigations, studies were performed on the cardio-vascular system, respiration, heat control, and the neuro-muscular apparatus of the animals. A block diagram of the on-board medical equipment used in these experiments is represented in Fig. 15, and its external view is shown in Fig. 16. The equipment is in the form of three blocks. The total number of measuring channels is equal to 15, including one channel for measuring 20 slowly changing parameters (physiological and hygienic characteristics and operating conditions of equipment).

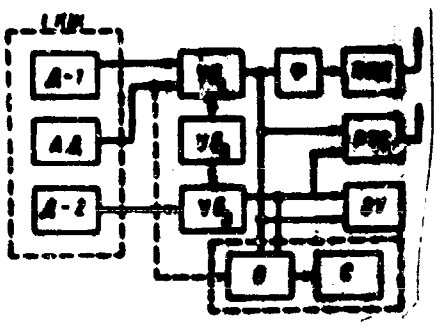

Fig. 15. Block diagram of physiological measurement system on second and third Soviet orbital spacecraft. ЖКЖ — animal capsule; Д (1, 2) — pickups; АД — automatic pressure control; УВ (1, 2, 3) — amplifying and switching blocks; Ф — square-pulse shaper; РТС — telemetry system; ПРД — transmitters; ЗУ — memory unit. Ground equipment; О — oscilloscope; С — automatic recorder.

The two measuring channels were designed for EKG recording. Since the investigations were conducted on animals located in a capsule, the noise level was insignificant and it was possible to use asymmetric amplifier circuits. The input impedance of the amplifier was 20-50 kΩ. The amplifier factor was 2000-3000. The frequency-response curve was rectilinear in a range of frequencies from 0.5 to 100 cps. The amplifier circuit had a 50 cps bandpass filter. One of the EKG amplifiers was connected to a special electronic circuit which separated the R-waves of the EKG curve, converted them into square pulses of about 100 milliseconds

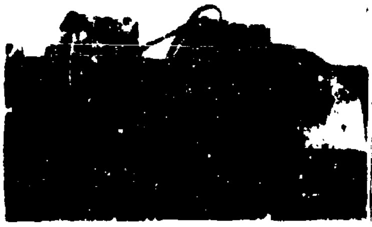

Fig. 16. External view of on-board physiological equipment of second and third Soviet orbital spacecraft.

in duration, and performed audio-frequency modulation. This circuit was intended for controlling the operation of the on-board transmitter for the purpose of checking the possibility of audio monitoring of the pulse frequency. Similar devices were subsequently employed on the "Vostok" spacecraft (electrocardiophone).

Measurement of arterial pressure was accomplished with the aid of an automatic device which provided cyclical compression of the carotid. Cuff pressure increased smoothly from 0 to 250 mm Hg for 30 seconds, and then there occurred a rapid drop in pressure. The pressure level was recorded by means of a micromanometer with conversion of the diaphragm position into voltage.

Oscillations in the pneumo-system, which were caused by pulse oscillations of the vascular wall, were converted into an electrical signal by a piezotransducer and amplified with the aid of an EKG amplifier. A similar amplifier was used to record the signals of the seismocardiographic transducer.

Identical amplifiers with a frequency response of 50-500 cps and an amplification factor of about 30,000 are used to record electromyograms and phonocardiograms. Inasmuch as both processes are relatively high-frequency, for the purpose of decreasing the capacity of the telemetering channel required for their transmission, are a detector and an integrator are connected to the input of the amplifiers (see Fig. 31).

A dc amplifier was used to measure temperature, to which thermistors in various parts of the body were alternately connected [8].

The Soviet "Vostok" Spacecraft

The first manned space flights, which were made in the "Vostok" spacecraft, made it possible to obtain a great deal of scientific data on the influence of various factors of flight on the human organism. Special completely transistorized radio-electronic medical equipment was installed to provide for reliable medical monitoring of the state of man and for solving research problems on board the "Vostoks." This equipment was modified from flight to flight by means of the addition of new blocks in accordance with changes in the flight program. The first equipment tests were conducted during the flights of the fourth and fifth Soviet orbital spacecraft [11, 193].

The equipment consisted of units which were placed in the cabin and in the astronaut's clothing. The cabin contained: the primary amplifying block, an electrocardiophone, and an instrument for recording galvanic skin reactions. The astronaut's clothing contained preamplifiers for recording kinetocardiograms, electroencephalograms, and electrooculograms. Pickups and electrodes were fixed by means of a chest harness. A block diagram of the physiological measurement system used in the experiment on the "Vostok-3" is represented in Fig. 17. Table 5 presents data on the methods of physiological measurement on the "Vostok" and "Voskhod" craft.

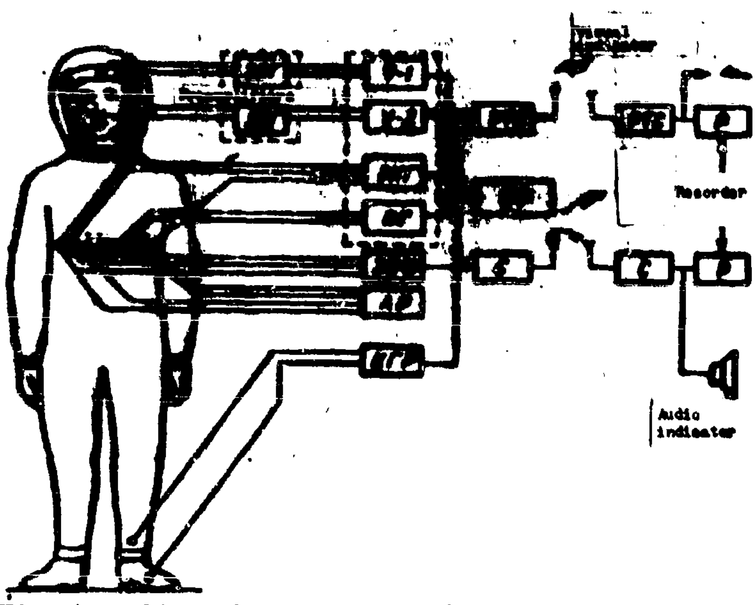

Fig. 17. Block diagram of physiological measurement system of "Vostok-3." У— amplifiers of primary block; ЭОГ and ЭЭГ – preamplifiers for recording electrooculograms and electroencephalograms; ЭКФ – electrocardiophone; АР— self-contained recorder; КГР – block for recording galvanic skin reactions; РТС— telemetry system; БР— on-board recorder; С— "Signal" transmitter; Р – recording device.

The primary amplifying block consists of three electrocardiographic amplifiers and one pneumographic amplifier. The characteristics of the amplifiers for recording electrocardiograms: amplification factor about 200; frequency response 0.5-40. The amplifier is symmetrical, which determines good noise immunity. Temperature compensation is ensured by the installation of a КМТ compensating resistor in each cascade. The pneumographic amplifier has an amplification factor of 20 and a frequency band of 0.1-15 cps. Its schematic diagram is represented in Fig. 26.

Table 5. Physiological Measurements on the "Vostok" and "Voskhod" Spacecraft and the On-Board Telemetric Equipment

Spacecraft	Pilot-astronauts	Physiological methods	On-board equipment	Sensors and electrodes
"Vostok"	Yu. A. Gagarin	Electrocardiography, pneumography	Primary amplifier block	5 electrodes for recording 2 EKG leads and a respiration pickup
"Vostok-2"	G. S. Titov	Electrocardiography, pneumography, kinetocardiography	Primary amplifier block and preamplifier for kinetocardiogram	The same + kinetocardiographic pickup
"Vostok-3"	A. G. Nikolayev I. R. Popovich	Electrocardiography, pneumography, electroencephalography, electrooculography, recording of galvanic skin reactions	Primary amplifier block instrument for recording galvanic skin reactions, and preamplifiers for electroencephalography and electrooculography	3 electrodes for electrocardiography, 2 electrodes for electroencephalography, 2 electrodes for recording galvanic skin reactions, and a respiration pickup
"Vostok-4" "Vostok-5"	V. F. Bykovskiy V. V. Nikolayev-Tereshkova	The same + seismocardiography	The same	The same + a seismo-pickup. In this flight the electrodes for electrocardiography and electrooculography were duplicated to increase the reliability of the measurement system
"Voskhod"	V. M. Komarov K. P. Feoktistov B. B. Yegorov	Electrocardiography, seismocardiography, pneumography, electroencephalography, electrooculography, dynamography, recording of handwritten signals	Primary amplifier block for medical monitoring + medical investigation block with commutation of 4 parameters in one channel	For medical monitoring, each astronaut continuously wore 3 electrodes for EKG, a respiration pickup, and seismo-pickup. The remaining electrodes and sensors were worn only during investigation

Preamplifiers which operated jointly with the EKG channels were used for electroencephalogram and electrooculogram recording. The preamplifiers provided 20-50 fold amplification of signals in a frequency band of 3-15 cps. The preamplifiers for the "Vostok-3" and the "Vostok-4" were a symmetrical with a self-contained power supply (1, 3, v). Both preamplifiers were placed in the astronaut's clothing; their size was just a little larger than a match box. The amplifiers employed in the "Vostok-5" and "Vostok-6" flights were symmetrical.

In the flight of G. S. Titov, an EKG amplifier together with a miniature preamplifier block the size of a match box was used for kinetocardiogram recording. This block was placed in a pocket of the pressure suit and provided amplification of the electromagnetic pickup signal from 10-20 μv to 1-2 μv [8].

The instrument for recording the galvanic skin reactions of A. G. Nikolayev and P. R Popovich consisted of a d-c measuring bridge with a self-contained power supply, a balanced modulator, a carrier-frequency generator (6 kc), an amplifier, and a demodulator. This setup recorded mainly slow (daily) changes in electrical resistance of the skin. In the flight of V. F. Bykovskiy and V. V. Tereshkova, an instrument of a different construction was used, which was designed to record mainly fast (reactive) oscillations of electrical resistance of the skin. The design of a similar instrument was initially developed by I. F. Akulinichev.

Continuous monitoring of pulse frequency during the flight of the astronauts on the "Vostoks" was carried out with the aid of an electrocardiophone (ЭКФ) [EKP], which is a device that converts electrocardiogram waves into square pulses 150 msec in duration.

The electrocardiophone includes: an amplifier, a limiter-shaper, a slave multivibrator, and an audio-frequency oscillator. The amplifier consists of two main parts: a differential biopotential amplifier and a shaping circuit. The differential amplifier is constructed like the input stages of an electrocardiogram amplifier, but has a frequency band of 10-20 cps. In the shaping part of the system, the wave is differentiated by a rheostat-capacitance circuit, amplified, and limited by a diode limiter. The obtained pulse triggers the slave multivibrator which generates time- and amplitude-calibrated pulses. This system of amplifying the pulse of an R wave and the selection of the place of installation of the electrodes at which the muscular potentials rendered a minimum influence on the magnitude of the input signal makes it possible to obtain reliable information on pulse frequency even during sharp motions of the investigated subject.

Soviet Multiseat "Voskhod" Spacecraft

The "Voskhod" spacecraft was the first multiseat rocket-powered flight vehicle. Its launching on 12 October 1964 was a veritable triumph of Soviet science and technology and opened an new era in the conquest of outer space. This step was very important from all points of view since only the daily collective work in space of many people and many space expeditions will allow man to become the true master of the moon, the planets, and outer space. The creation of a crew with the participation of a physician will allow to use a new principle for collecting biomedical information which is based on the separation of questions of medical monitoring and medical investigations (this will be discussed in detail in the following chapter). A physiological measurement system was correspondingly built on the "Voskhod." The radioelectronic medical equipment consists of two blocks, one of which was designed for continuous medical monitoring of all three astronauts simultaneously and the other was turned on periodically when carrying out medical investigations. The medical monitoring block consisted of six amplifiers, three of which were designed to record electrocardiograms, while the other three made it possible to record seismograms and pneumograms on one channel. In addition, the same block contained a pneumoelectrocardiophone with a commutator. This new system was constructed on the basis of the experience of using the electrocardiophone on the "Vostoks." The pneumoelectrocardiophone has control of the duration of the pulses shaped by it from heart biopotentials with the aid of a contact respiration sensor. On inhalation, the pulse width is 150-200 m/sec, and on exhalation it is 70-100 m/sec. This ensures operational monitoring of both pulse rate and respiratory rate. Transmission is accomplished through the on-board "Signal" system. A special commutator connected one of the astronauts to the pneumocardiophone and sent a corresponding marker signal every two minutes.

Information was collected by means of a chest harness with electrodes (DS lead) built into it, a seismocardiographic sensor, and two respiration sensors (carbon and contact).

The research system was designed for consecutive recording (through one telemetering channel) of electroencephalograms, electrooculograms, dynamograms, and hand-written signals (objective recording of writing). The sensors and electrodes were attached by the physician only during the period of investigation were conducted in several revolution at different flight times.

American Biomedical Experiments on "Jupiter" Ballistic Rockets

In 1958-1959 American scientists carried out two flight experiments on "Jupiter" ballistic rockets [461, 523].

Six telemetering channels were used to transmit physiological data to Earth. An electrocardiogram, a phonocardiogram, and two electromyograms were transmitted through independent channels. The remaining parameters – body temperature and respiratory rate, humidity, pressure, air temperature, and carbon dioxide content – were transmitted through a commutator. The amplifying equipment was transistorized and had a printed circuit.

Amplifiers for electrocardiogram recording had an amplification factor from 1000 to 5000 with an input impedance of up to 100,000 ohms. Frequency response was rectilinear in a range from 1 to 750 cps.

Phonocardiogram recording was carried out with the aid of an amplifier with a frequency band of 20-2000 cps and an amplification factor of 1500. A microphone with 20,000 ohm resistance provided a signal of the order of 5-10 mv at the amplifier input.

Each of the two amplifiers of muscle biopotentials had an input impedance of about 100,000 ohms, a frequency-response curve of 10-2000 cps, and an amplification factor of 300.

Thermistors which were connected to the circuit of the stabilized supply source were used to record the respiratory rate and body temperature. They provided an output signal of the order of 0-5 v without special amplifiers.

American Research in the "Mercury" Program

The first tests of the physiological equipment of a "Mercury" capsule were conducted during the flight of the chimpanzee Ham on 21 January 1961 [788]. The equipment was subsequently improved by means of the gradual addition or replacement of sensors and blocks. The equipment initially consisted of two electrocardiographic amplifiers and circuits for measuring body temperature and recording respiration by thermistor pickups.

Stainless-steel disk-shaped electrodes with a 30-mm diameter were used for electrocardiogram recording. The electrodes were built into a rubber ring which was secured to the body by means of a patch. Respiration was measured by means of a thermistor that was heated to a temperature of 93.3°C and placed in one of the microphones. For temperature measurements, a 3-mm catheter was constructed which contained a thermistor connected to a bridge (frequency 400 cps). In G. Cooper's

flight, body temperature was measured by a sensor which was periodically placed in the mouth, instead of a rectal thermistor [788]. In J. Glenn's first orbital flight a system for measuring arterial pressure according to the Korotkoff method was employed. In this case, however, the astronaut had to compress the cuff himself [789]. Measurement of arterial pressure was fully automated in Carpenter's flight. The cuff for its measurement was placed on his left arm. A microphone was built into the lower part of the cuff. The microphone was piezoelectric with a diameter of 3.5 cm and a thickness of 0.5 cm. An amplifier with a frequency band of 32-40 cps was employed to decrease interference and noise [445]. The amplifier was cut off in the absence of a signal. Beginning with W. Schirra's flight, the method of impedance penumography was used to record respiration [790].

The medical equipment for the "Mercury" capsule was developed by the McDonnell Corporation [788]. The equipment was completely transistorized with the use of printed circuits.

On-Board Systems for Data Transmission and Recording

The transmission of data a spacecraft to Earth is carried out with the aid of various types of radio systems. Of prime value in space physiology are radiotelemetry devices; however, in the overall composition of the devices in a physiological measurement and information system a definite role is also played by other systems of data transmission and recording: communications equipment, television equipment, and memory units. A consideration of a contemporary physiological measurement system on a spacecraft is impossible without investigating the role of each of these systems.

On-Board Radio Telemetry System

The telemetering device converts the output signals of the on-board physiological equipment into radio signals of a specific form. The same transmitter of the spacecraft simultaneously transmits a large number of technical and biological parameters. To create a complex telemetering signal which carries information on a large number of parameters, the on-board system has a modulator or encoder, and the ground system has a demodulator decoder. According to the methods of channel separation, multichannel telemetering systems are divided into systems with frequency separation, by time separation, and code separation [43].

The method of frequency modulation consists in the fact that the subcarrier frequency for each parameter is separated, which varies in accordance with the

magnitude of the measured parameter. The methods of time modulation can be based on the transmission of pulse through a radio channel: 1) the duration of the pulses depends on the magnitude of the measured parameter at specific moments of time (pulse-width modulation – (ШИМ) [PWM]); 2) the time between pulses (pedestal and measuring pulses) is a function of the measured magnitude (pulse-time modulation – (ВИМ) [PTM]). In code modulation, separate values of the measured magnitude are converted into a code, e.g., into binary numbers, which are transmitted in the form of pulse groups. Figure 18 shows a diagram of the shaping of telemetric signals with the var us modulation methods.

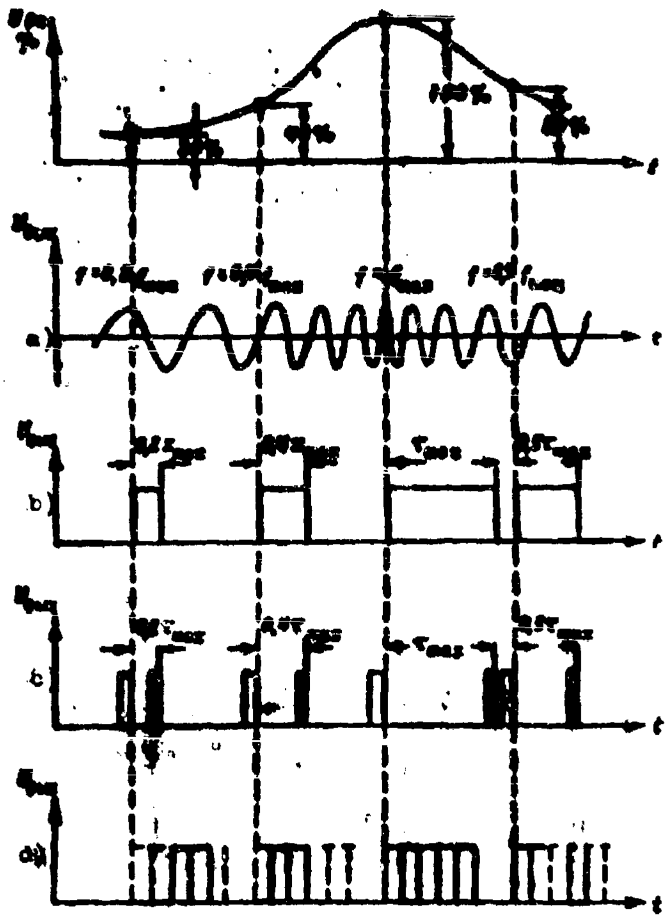

Fig. 18. Shaping of telemetric signals. a) frequency modulation; b) pulse-width modulation; c) pulse-time modulation; d) pulse-code modulation.

On the basis of considerations of economy, noise immunity, reliability, and effectiveness, systems with time separation are used most frequently in astronautics.

Special commutators which alternately connect the outputs of different channels to the radio system are employed for transmitting a large number of different parameters on one carrier frequency. The frequency of connection is from one to hundreds of times per second [14]. Mechanical commutators are used for small low of interrogation, and electronic ones are employed for high speeds. Thus, the radio channel receives discrete values of the measured quantities, and they are recorded on Earth also in discrete form in the shape of a curve consisting of separate points whose amplitudes correspond to the voltage of the channel and whose frequency corresponds to the commutation frequency at the output of the telemetering system.

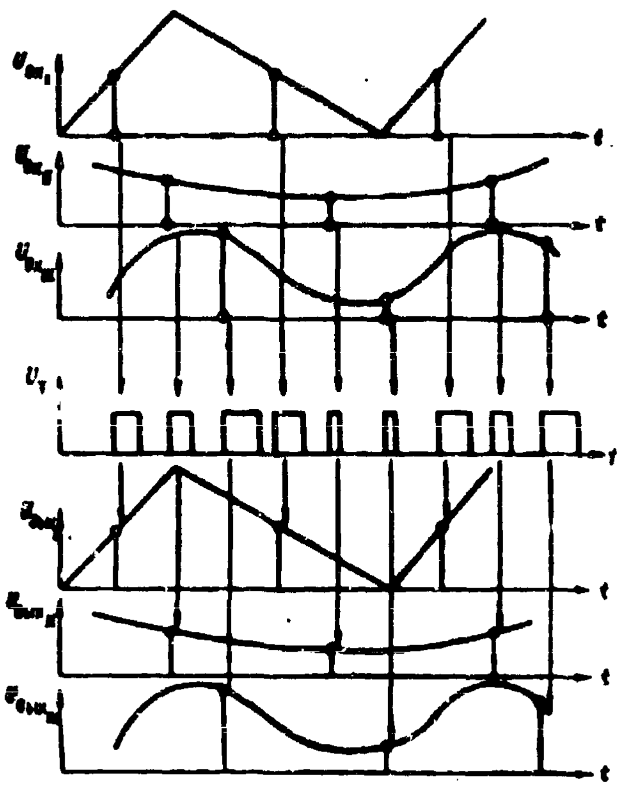

Fig. 19. Shape of telemetric signals transmitted by a multichannel system with pulse-width modulation.

Figure 19 shows a diagram of the shaping of a telemetry signal in a multichannel system with the pulse-width method of modulation PWM. Actual PWM systems do not permit the arbitrary selection of the most optimum frequency of interrogation for each channel. There is a certain standard interrogation frequency for all channels, and it can be increased only by means of connecting several channels in parallel, and decreased by using additional commutators at the input to the telemetering channel. It is also possible to employ methods of storing information in a channel by means of simultaneously recording several parameters (111, 173, 254, 548).

The radiotelemetry systems that are utilized for transmitting physiological information from a spacecraft to Earth can be divided into: a) periodic-action systems of direct transmission; b) continuous-action systems of direct transmission; c) systems with storage and subsequent transmission of information [32].

At present, space physiology uses mainly systems of direct transmission. Transmission is carried out in orbital flights, in periods when the spacecraft passes over corresponding measuring points. A "Signal" transmitter was used for continuous

direct pulse transmission on the "Vostoks." It operated during the entire time of flight, emitting pulses in the rhythm of the astronaut's heart contractions.

On-Board Data-Storage Systems

Information is stored on board in the following cases: a) if it is necessary to perform measurements in such periods of time when the telemetering system is not operating, e.g., beyond the sphere of action of the receiving stations or during the time of descent; b) if the total capacity of information sources in the period of measurements exceeds the capacity of the telemetering system; c) if the total capacity of the information sources is considerably lower than the capacity of the telemetering system and there is not enough power to transmit information in the process of measurement; d) if it is necessary to duplicate data recording by radiotelemetry with recording on board the spacecraft.

The systems that are utilized for storing physiological information can be divided into the following groups:

1) long-term storage devices (information is read after the craft returns to the ground); 2) operational storage devices; a) with accelerated reproduction; b) with delayed reproduced; 3) intermediate memory systems for data storage in the process of transmission or recording.

This classification of on-board memory units has an analogy in the theory of digital computers. In this case there also are three corresponding types of memory units: the long-term memory, the fast-store memory, and registers (buffer memory units).

Biomedical space research is presently employing mainly long-term memory devices. Fast storage with accelerated reproduction was used only for transmitting information and performing various physchological tests recorded by an on-board tape recorder.

An on-board magnetic-tape memory device with a high recording density was used to record physiological data during the descents of the second through fifth Soviet orbital spacecraft and the "Vostoks." After the flight, the information from the magnetic carrier was re-recorded on photographic or paper tape for subsequent analysis. A miniature self-contained recorder which was placed in the astronaut's clothing or in his parachute bag [11, 294, 295] was used to record important physiological data (pulse and respiration) after the astronaut had ejected. Recordings obtained with the aid of a self-contained recorder make it possible to investigate the physiological reactions of an astronaut at the time of ejection, and during parachuting and landing.

Memory units may be characterized by their storage capacity and speed. The storage capacity is the total amount of information computed in bits, for example, which the memory can contain at maximum storage. The storage speed is analogous to the concept of the carrying capacity of a radio channel. It is necessary that the capacity of the information source be coordinated with the storage speed. To prevent possible distortions in the storage process, it is necessary that its speed be somewhat higher than the speed of information input. Thus, for storing an electrocardiogram (the amount of information is approximately 500 bits/sec) the storage speed should be no lower than 600 bits/sec.

Calculation of the capacity of memory units in relation to the capacity of information sources has an important value in fast-store memorization. Here it is necessary to consider the amount of information to be stored, the speed of data input and output, and the time of recording and reproduction. All these indices must be mutually coordinated. Fast-store memorization of physiological information has a big future in prolonged and distant space flights. A characteristic of systems with accelerated reproduction is the dependence of the amount of information introduced per unit of time on the periods of storage and reproduction. If a standard telemetry channel is used for reproduction and the reproduction time is equal to 5 minutes, for example, a simple calculation shows that storage takes 60 minutes, which means that the speed of information input to the memory unit should be 12 times less than that in direct transmission. Accordingly, an increase in the storage period to twenty-four hours leads to practically a 300-fold (12×24) decrease in the amount of information stored per unit time. Thus, the use of data-storage systems with subsequent reproduction of information envolves the problem encoding biomedical data. This problem becomes even more serious if we consider that with the increase of the duration and distance of space flights, the capacity of direct-transmission will decrease, which, in turn, will lead to larger limitations on the possibility of transmitting biomedical information. An important role must be played here by memory units with delayed reproduction. For instance, if the carrying capacity of a radio channel is insufficient for direct transmission of an electrocardiogram (for instance, a channel with a capacity of 10 bits/sec), the electrocardiogram can be introduced with normal speed (500-600 bits/sec) into the on-board storage device, and then transmitted with a 10-fold deceleration through an available telemetric channel. The transmission of a one-second segment of an EKC curve will then take 60 sec.

Table 6 lists tentative data on the necessary factors of acceleration or

acceleration of transmission of physiological information with the use of telemetering channels with different carrying capacities from 0.01 to 500 bits/sec. A fraction indicates the necessity of slowing down transmission (the denominator shows the multiplicity of deceleration). The integers correspond to the number of seconds of actual recording of the amount of information which can be transmitted through a given channel in a direct-transmission mode per second. One may see from the table that an electrocardiogram can be transmitted through a channel with a carrying capacity of 20 bits/sec with approximately a 25-fold delay, and the data of 200 temperature measurements can be transmitted in 1 second.

Table 6. Tentative Data on Capacity of Memory Units (ЗУ) [MU] and Characteristics of Modes of Accelerated and Delayed Reproduction of Physiological Information

Characteristics of MU and operational modes	Physiological Parameters			
	ЭЭГ	ЭКГ	ПГ	ТТ
MU capacity for storage period				
–2 min	60 thous.bits	30 thous.bits	1200 bits	6 bits
–20 min	600 thous.bits	300 thous.bits	12 thous.bits	60 bits
–1 hour	3 mil.bits	1.5 mil.bits	60 thous.bits	300 bits
–8 hours	24 mil.bits	12 mil.bits	480 thous.bits	2400 bits
–24 hours	72 mil.bits	36 mil.bits	1 mil. 400 bits	7200 bits
Deceleration and acceleration factors of transmission for radio channels with the following carry-capacities				
–0.1 bits/sec	1/10000	1/5000	1/200	1
–1 bits/sec	1/1000	1/500	1/20	10
–20 bits/sec	1/50	1/25	1	200
–100 bits/sec	1/10	1/5	5	2000
–500 bits/sec	1/2	1	25	5000
–1000 bits/sec	1	2	50	10000

Note: (ЭКГ) [EKG]— electrocardiogram; (ЭЭГ) [EEG] — electronencephalogram, (ПГ) [PG] — pneumogram, (ТТ) [BT] — measurement of body temperature.

The table also gives calculations of storage capacity for various storage times.

Questions of on-board storage and transmission of physiological information to Earth are closely related to investigations of the informational characteristics of physiological parameters. Under laboratory and ground conditions it is usually not necessary to scrupulously coordinate the amount of information with the capabilities of the recording instrument, where frequently a narrowing of the frequency band (i.e., a decrease in capacity) of the channel is only the means of counteracting interferences. Conversely, physiological measurement systems on a spacecraft must be constructed taking into account their main requirement of transmitting (recording) maximum information with the use of the minimum capacity

of the telemetric (recording) channel. This requirement eventually causes essential changes, as compared to conventional ones, in the methods of collecting information in the circuits of electronic amplifier equipment. Moreover, the observance of this requirement necessitates the development of absolutely new methods of physiological investigation. Also very significant are the changes introduced by the specific character of transmission and storage of information in space flight, the methodological principles of the physiological investigations, their organization and preparation, processing the results of measurements, and analyzing them.

Television and Radio Communications Systems

A considerable amount of physiological information has been obtained during space investigations by means of television and radio communications. The clarity of the television transmissions during the flights of "Vostok 3-6" made it possible to analyze the astronaut's facial expression and his oculomotor responses. In flight experiments with animals, television was used to observe the motor responses of dogs in various phases of flight [77, 117]. The Soviet spacecraft had two television cameras which made it possible to conduct extensive observations. Figure 20 shows samples of television pictures that were obtained during investigations with animals and in the "Vostok" flights.

Fig. 20. Samples of television pictures obtained during flight experiments with animals and in "Vostok" flights.

The television method of investigation and monitoring is now being employed more and more in medicine and physiology. Television is used in operations for observing difficult cases and for investigations in microbiology, opthalmology, and

other fields [60]. The television method in space physiology obviously has a big future. A large number of remote investigations, such as endoscopy, examination of the ocular fundus, study of pupil reflexes, diagonosing of skin diseases, and so forth, will become possible, especially with the introduction of color television.

Television makes it possible for a physician to observe his "space patient," while radio communications permits him to hear the patient and converse with him. Certain authors ascribe an exceptional value to two-way radio communications with the astronaut, considering its role in providing operational medical monitoring no less important than electrocardiography [405, 669]. According to the data received from radio conversations, the physician can estimate the general state, efficiency, and health of the astronaut, his neuro-emotional background, and also can detect mental disturbances. It is necessary to distinguish two methods of radio-conversation analysis: 1) the local-semantic method, when prime importance is ascribed to what the astronaut says and how he answers questions; 2) the structural-acoustical method, when such informational characteristics of speech as frequency spectrum, fundamental and component harmonics (timbre), duration of separate sounds, words, and phrases, and other indices are taken into account. Consequently, physiologists and physicians are extremely interested in high-quality and noise-proof communications. For semantic communication, it is sufficient to use a narrow frequency band within the limits of a hundred cycles per second, while a structural-acoustical evaluation of an astronaut's speech requires a sufficiently broad dynamic frequency band, e.g., from 100 to 7000 cps or even from 20 to 20,000 cps.

During the "Vostok" flights, an extensive network of ground shortwave and ultra-short wave stations was used for two-way radio communications. On board there were primary and reserve radio sets of different ranges. Microphones, laryngophones, and telephones were placed in the astronaut's helmet. In addition, extra microphones and loudspeakers were installed in the cabin. This made it possible to continue radio communications when the astronaut left his seat and when his spacesuit was disconnected from the on-board cable network. In these moments of flight, information from the sensors and electrodes did not enter the channels of the telemetry system and radio communications was the only method for evaluating the astronaut's condition.

The radio communications equipment of the spacecraft had both automatic and manual control. The astronaut could regulate the volume of the receivers, turn the transmitters on and off, and connect the microphones and telephones. A physiological evaluation of these operations can be of importance for investigations of

astronaut efficiency in flight.

Radio communications, television, and radiotelemetry, by complementing one another, compose the single foundation of the contemporary physiological measurement system on spacecraft [5, 9].

Problems of Preparing and Conducting Height Experiments and Evaluating Their Results

Among the various investigations in the field of space biology and medicine, a central position is occupied by the flight experiment. The direct result of each flight experiment contains a definite amount of scientific information. The quality and quantity of this information depends not only on the theoretical level of the development of questions on data transmission, the selection of research methods, and the creation of appropriate equipment, but also to a considerable extent on how practically the flight experiment is prepared, how is medical security in the course of flight organized, and how the obtained data are processed. Therefore, an account of the questions of preparing and carrying out flight experiments and evaluating the results is organically related to the investigation of a contemporary physiological measurement system on a spacecraft. The recipient of the information (physician, physiologist) is one of the objects of the physiological measurement and information system to the same extent as the source of information (astronaut). A consideration of this system would be incomplete without studying the problems of feedback.

In this case these problems are related to the specific state of the astronaut before, during, and after the flight the making of decisions and the issuance of instructions on the basis of the results of medical monitoring, and the making of recommendations on preparation for the following flight experiment.

Preflight Testing of Physiological Measurement System

As it is known, a measurement process requires the presence of two quantities: the one to be measured and a standard. Standard information is extremely important for physiological measurements in a space flight in view of the peculiarities of the research methods and equipment plus the variety of conditions of the experiment itself. Preflight testing of the physiological measurement system is one of the sources of standard information. The following functions are performed in the testing process: a check of methodological methods and equipment; individual finishing of electrodes and sensors in reference to the specific astronaut candidates; obtainment of the reference data necessary for subsequent analysis of telemetric information

training of astronauts; a check of the efficiency of the physiological measurement system in a laboratory experiment with maximum approximation to flight conditions; preparation of medical staff for work in prelaunch period and during flight.

Preflight tests are conducted with the application of stationary, clinical, and permanent on-board equipment. In the beginning, the methods proposed for inclusion in the flight experiment program are studied with the use of stationary equipment. Then, by modifying the sensors and electrodes, they try to obtain high-quality recordings which are subsequently considered to be the standards. Further, in the process of testing a mockup of the on-board equipment, they try to obtain recordings of analogous quality. Then, on the permanent on-board equipment, after individual finishing of system of securing the electrodes and sensors, physiological functions of the astronauts are recorded, bearing in mind the standard recordings obtained previously. The obtainment of high-quality recordings of physiological functions in the pre- and postflight period is of importance for evaluating the information recorded directly in the course of flight. Therefore, serious attention is given to all stage of preparation for the flight experiment.

Special devices have been developed for carrying out the various testing operations, which involve individual finishing of sensors and electrodes, checking out the physiological equipment, and carrying out self-contained and full-scale tests of the physiological measurement system: a test panel and a simulator [11]. The test panel is used to check the quality of fixation of the sensors and electrodes without the on-board equipment. This check is extremely necessary in the various stages of work and especially in process of outfitting the astronaut on the day of the launching. Since the launch preparation is conducted on a strict time schedule, a delay in outfitting the astronaut is impermissible. If a wire break or improperly-locates sensor is detected after the spacesuit is put on, and all the more so after sitting down in the cabin of the spacecraft, correction of the situation may demand rescheduling of the day of the launching. Therefore a test panel in the form of an analog of the on-board equipment is an important aid to the physician. It consists of two amplifiers and a switching device, and makes it possible to monitor the operation of the electrodes and sensors by means of a dynamic loudspeaker (for listening) or a microammeter (visually). A second simulated instrument is an analog of the information source. Recently in literature there have appeared descriptions of simulators for medical purposes [655, 690] and analog computers, which also are simulators [3]. A simple simulator can be made in the form of a neon-tube relaxation generator. The generator sends out acute-angle pulses like the R waves of an

electrocardiogram. Their tracking frequency is continuously regulated by means of a potentiometer of intermittently by means of capacitance switching. Practically square pulses are given by a transistorized multivibrator-type simulator. More complicated simulators permit recording of pulses of various, frequently rather complicated, form simultaneously through several channels (Fig. 21). The magnitude of the output signal is selected with the sensitivity thresholds of the input of the amplifier of the channel under investigation. It is usually sufficient to have two standard values of output signals: 100 microvolts and 1 millivolt. Simulators are extremely useful in various checks of the on-board equipment, but are especially important during prolonged technical tests.

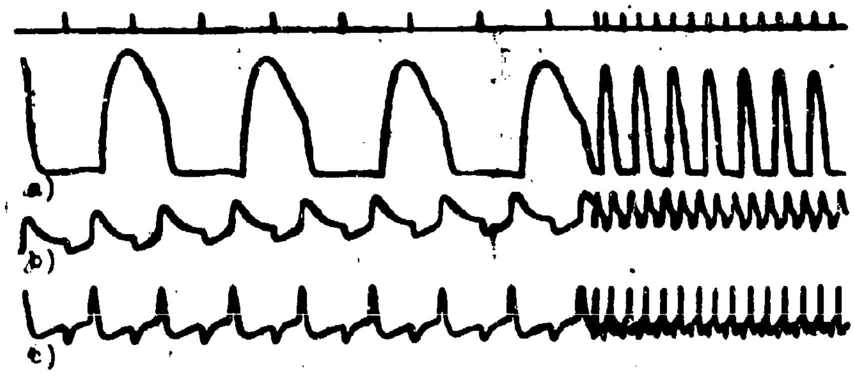

Fig. 21. Samples of simulator output signals which simulate a pneumogram (a), a sphygmogram (b) and an electrocardiogram (c).

When considering questions of the collection of reference data which will subsequently serve as a standard for evaluating telemetric information, it is necessary to indicate the following circumstance. A distinctive feature of the physiological measurement and information system of a spacecraft is the polygraphic approach to the investigation of physiological functions. Laboratories and clinics presently are mainly using the method of independent study of separate systems and organs, e.g., there are electrocardiographs and corresponding electrocardiographic departments, electroencephalographs and corresponding electroencephalographic departments. Even the departments and sections of functional diagnostics are equipped with a large number of various devices which are used separately depending upon the readings during the examination of one patient or another. High-quality mass-produced instruments are used for the preflight examination of astronauts: encephalographs, spirometablographs, mechanical cardiographs, and so forth [294,

295]. However, to obtain data in accordance with the methodology of the full-scale approach to physiological investigations in flight, it is necessary to construct appropriate equipment [474, 11, 294].

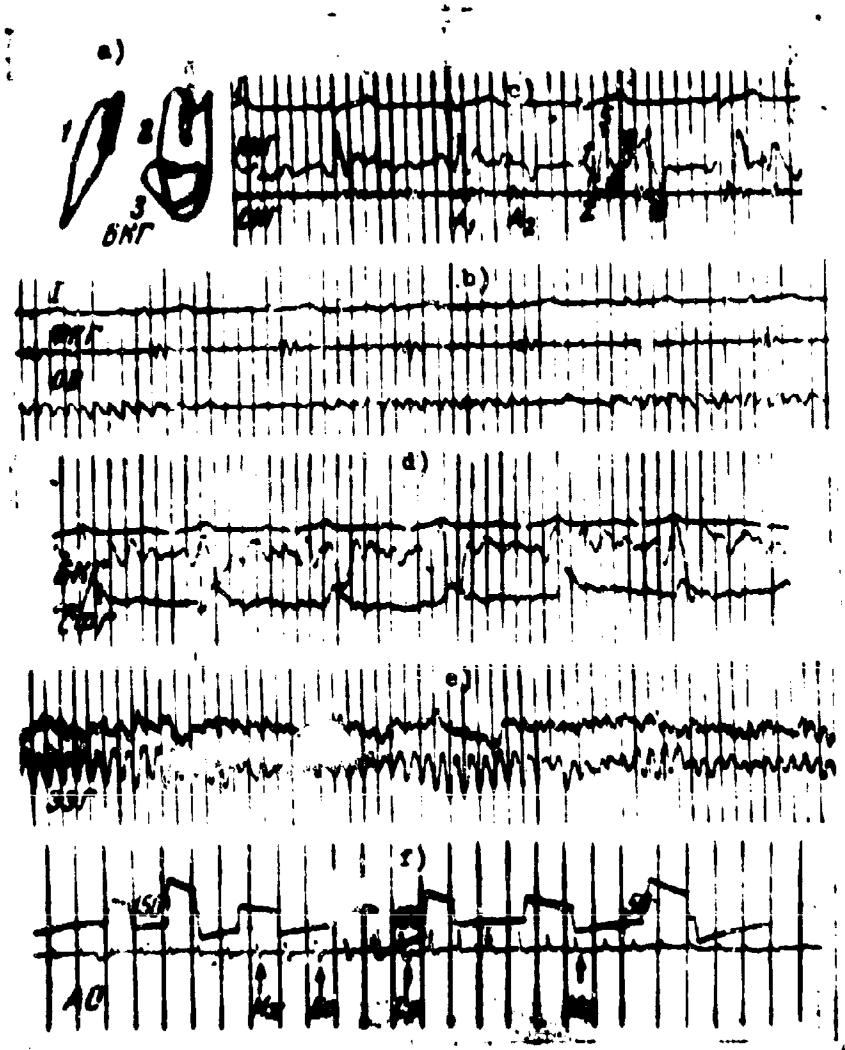

Fig. 22. Samples of recording of various physiological functions with the aid of a "Zemlya"-type instrument. a) ВКГ (vectorcardiograms): 1, 2, 3 — frontal saggital, and lateral projections; b) ФКГ (phonocardiogram), I — electrocardiogram in first lead; ОД — volume respiration (pulmonary ventilation), c) ККГ (kinetocardiogram), СКГ (seismocardiogram); d) БКГ (ballistocardiogram), СФГ (sphygmogram); e) ЭЭГ (electroencephalogram); f) АО (arterial oscillogram). The readings of maximum (Мх), lateral mean (Бо) — mean dynamic (Ср), and minimum (Мн) pressure are indicated with arrows above the pressure marks and below them.

The (ЭМА) [EMA] plant, together with our participation in cooperation with I. T. Akulinichev, developed a "Zemlya"-type instrument for full-scale polygraphic research which was used under clinical and polyclinical conditions, and was also

applied in prelaunch investigations. Figure 22 illustrates samples of recordings of various physiological functions that were made with its aid. The described instrument was constructed on the basis of the vectorcardioscope designed by I. T. Akulinichev and makes it possible to conduct both visual observation and recording of parameters on 36-mm photographic film. The total number of physiological parameters which can be recorded in a full-scale investigation is 16, including an electracardiogram, vectorcardiogram, phonocardiogram, arterial oscillogram, ballistocardiogram, electroencephalogram, body temperature, galvanic skin reflex, conditioned more responses, and so forth.

A similar "combine" essentially replaces the department of functional diagnostics and makes it possible to conduct extremely diverse physiological research according to a selected program.

Medical Monitoring During Space Flight

The medical check of an astronaut on the day of a flight begins with an evaluation of prelaunch recordings. After the astronaut enters the spacecraft during the launch preparation, practically continuous recording of the most important physiological parameters is conducted (electrocardiogram, pulse rate, respiratory rate). Of importance for providing medical monitoring in the prelaunch period are two-way radio communications with the launch command post and periodic observations on a television channel.

At the time of launching and during propelled flight, thorough medical monitoring is conducted according to television data radio conversations, and also by means of visual monitoring of the main physiological parameters on the screen of the telemetry station.

After the spacecraft is launched, the network of ground telemetry measuring points begins to operate. At each point there is a medical group, whose duties include medical monitoring at the moment that the spacecraft flies over a given point and immediate transmission of data to the flight control center and to the coordination-computation center. Thus, for the flights conducted under the "Mercury" program, 15 receiving stations located in various areas of the world in the orbital projection of the spacecraft were connected with the launch center at Cape Canaveral (Cape Kennedy).

In the USSR, during the flights of the second through fifth Soviet orbital spacecraft with animals, for the purpose of obtaining experience in medical monitoring, medical groups were set up for operational evaulation of the state of the animals

in space flight.

The specific character of the work of the physicians at the measuring points demanded special training and instruction on how to read telemetry recordings. For operational evaluation of data obtained in the course of flight, special tables were constructed which systematized the data of the training and attempts of each astronaut that made a flight. Thus, tables were constructed with data on the limits of individual variations of the basic physiological indices during the action of G-loads, during heat tests, during prolonged isolation, and so forth. A great deal of assistance was rendered also by graphs of the changes in pulse and respiration where observed in preceding space flights and tests. These data were considered to be the standards when comparing them with the results of the flight of other astronauts. Indeed, every subsequent flight essentially differed with respect to time from the preceding one, but even a comparison of the physiological reactions in identical phases of flight was an important factor for a proper medical evaluation of the data and a prognosis.

In the process of preparation for work at the measuring points, the various dangerous deviations in the state of health of the astronauts that are probable in flight were studied and the possible pathological changes of the recorded parameters were schematically depicted.

Medical monitoring at the measuring points were carried out in two stages. The first stage consisted of visual observation of physiologocal indices (basically electrocardiograms and pneumograms) on the screens of telemetry devices, listening to (and counting) the electrocardiophone signals, examining television pictures, and monitoring the content of radio conversations. On the basis of these data, a preliminary conclusion was made concerning the state of the astronaut. The second stage of operational monitoring consisted of a more detailed study of telemetry recordings, and an exact determination of the pulse rate and respiratory rate, the hygienic conditions in the cabin, and the radiation situation. These data were transmitted to the flight control center and to the coordination-computation center. The conclusions concerning the state of astronauts were made on the basis of calculating all the data and comparing them with the data from ground tests and training sessions.

A final conclusion about the state of the astronaut was made by medical specialists and consultants in the medical groups at the flight control center and the coordination-computation center.

We should point out some of the peculiarities of the reception of telemetry information from a spacecraft which interfere with the realization of medical monitoring. The fact is that the motion of a craft in orbit stipulates only an episodical character of communication with Earth. The amount of information obtained during a space flight is severely limited; the duration of recording periods depends on the orbital parameters, the location of the receiving points, and also on the power resources of the spacecraft. The communication time in different revolutions of an artificial satellite, and consequently, the amount of information obtained, are not identical. At separate intervals of time up to several hours in length, direct telemetry communication is impossible and only the medical information are the signals from the continuously operating electrocardiophone (the "Signal" transmitter). Part of the biological information is recorded on board the spacecraft and cannot be obtained in the course of the space flight. This information is on the descent phase. Thus, the physicians must deal with information obtained from various flight phases that is nonuniformly distributed in time and quantity, which creates definite difficulties in its processing and analysis. In addition, the form of data recording sharply differs from the usual laboratory oscillograms. It is usually photographic film with recordings in the form of points with curves. The frequency of quantification and the accuracy of reading depend on the capacity of the telemetry channel. Tapes with recordings are marked with a single time (Moscow) which makes it possible to synchronize the data of several channels or even the receiving points, and to accomplish time annexation to the data obtained through the radio communications and television channels. In the beginning and at the end of the information reception period, due to radio interference, data interpretation and analysis are difficult.

In the process of medical monitoring it is difficult to perform complicated statistical calculations; however, a specific amount of measurements is necessary. As a rule, the mean maximum and minimum values of separate indices are determined for each revolution, and the entire volume of information is quantitatively evaluated on the object of manifestation of specific changes in the oscillograms. Of importance is a comparative analysis of data from revolution to revolution. This results in the timely detection of tendencies toward the appearance of pathological deviations and an appropriate prognosis can be established.

The participation of a physician in a space flight does not essentially change the general principles of medical monitoring at least for the closer orbital flights. The physician-astronaut, just as the rest of the crew, must be monitored by the medical

staff on Earth. Therefore, the entire system of medical monitoring described above also remains unchanged for flights of multiseat craft with a physician on board. However, it is natural that the reliability of monitoring is essentially increased here. Many dangerous situations can be quickly detected by the physician and fast medical aid can be given both on the basis of the results of the physician's observations and also on the basis of instructions from Earth. When the spacecraft has on-board computers, the diagnostic capabilities of the physician are considerably increased in flight and the intensity of work of the ground staff decreases.

The use of computer technology on Earth for current operational analysis of information in the course of space flight will also be of importance. Such experiments already are being conducted. There is also a number of experimental and theoretical efforts in this direction, which indicate the expediency of constructing automated ground systems of medical monitoring [376].

Evaluating the Results of Flight Experiments

Spacecraft flights to some extent experimentally confirm specific calculations and laboratory investigations, which in turn are based on the experience of previous flight experiments. As indicated above, there is feedback in the system of the following categories: theoretical investigations and calculations, laboratory experiments and mockups; experimental space flights. This means that the results of every flight experiment have a high scientific value and should serve as the basis for the organization and realization of subsequent, more complicated, flights into space. In reference to questions of physiological measurements, the analysis and evaluation of telemetry information obtained in the course of flight have two aspects: the obtainment of new scientific data on the influence of factors of space flight on a living organism; the obtainment of information on the quality of operation of the physiological measuring system, data on the effectiveness of the methods used, and determination of ways of further improving the measurement system.

It is naturally that these two aspects are interdependent and supplement one another, since it is impossible to imagine the possibility of proper scientific treatment of flight data without a knowledge of the methodological peculiarities of the measuring system, and conversely, it is impossible to estimate the effectiveness of the physiological methods used and to outline ways for their improvement without knowing the scientific results of the flight.

Questions of the evaluation of telemetry information have a specific character both due to the peculiarities of obtaining information (time and quantitative

nonuniformity) and also because of its huge volume. Since the actual formulation of space experiments is not within the capability of one person, even a simple examination of many kilometers telemetry recordings, not to mention their processing and analysis, is impossible for one person to accomplish. The data obtained as a result of the realization of a space flight experiment are the property of everyone that has participated in its preparation and performance. The first experience of processing and analyzing large amounts of telemetry information was obtained during flight experiments on the second and third Soviet orbital spacecraft with animals. The method given below was developed in cooperation with G. N. Zlotin.

In the postflight period, all telemetry recordings obtained at the various receiving points were concentrated in one place. The first stage of operation was to n te and fix the time of the recordings and then to construct so-called receiving chains. A receiving chain is continuous series of telemetry tapes obtained during one communication period. Since numerous stations are operating during the period, partially duplicating one another, the task consists in selecting the best quality recordings. All further treatment is conducted within the limits of the receiving chains.

Primary interepretation of recordings consists of determining certain amplitude and time indices. In the beginning of the operation, medical specialists make up the so-called telemetry information interpretation plan, which indicates:

a) a list of the measured indices for each recording channel; b) the procedure for determining each index; c) the frequency of measurements; d) the methods of calculating the necessary derivatives.

As a result of the primary interpretation, numerical data are obtained with a specified discretion which characterizes the measured physiological parameters.

However, the huge amount of data cannot be analyzed without the appropriate grouping and statistical processing [209].

For data grouping, the qualitative uniformity of the data should be taken into account. Grouping of data obtained by telemetry was produced in accordance with flight phases in which qualitatively (but not quantitatively) uniform influences are expected. There are four of these phases: ПС — prelaunch; A — powered flight; O — orbital; C — descent. However, nonequivalent conditions were observed practically in each of the mentioned phases. Thus, in the powered-flight phase, the magnitude of accelerations acting on the living organism at different times from the moment of launching was different. Reactions to weightlessness also to a considerable extent

depend on time. Therefore, when the recordings were processed, phases ΠC_1 and ΠC_2 were isolated; ΠC_1 was 3-4 hours before launching; ΠC_2 was 5 minutes before launching; A_1 and A_2 were the first and second half of powered flight; H_1 was the first five minutes of weightlessness; H_2, H_3, and H_4 were the following 5-minute periods of o .cal flight in the first revolution. The information obtained in each revolution of the spacecraft around Earth was grouped according to revolutions (B_{2-16} etc.). In the descent, data grouping was carried out in 5-minute intervals (C_1, C_2, C_3, etc).

Let us consider the rules of the proposed method of grouping telemetry data. First of all, one should note that for the prelaunch, powered flight, and descent phases, all the data to be analyzed is generalized. However, here we are concerned with an evidently nonstationary nonergodic process. Therefore, the averaging times should be selected as minimum, e.g., equal to 10 sec, i.e., such, within the limits of which the conditions of stationarity are observed. In the orbital phase of flight, within the limits of the operating period of the telemetry receiving point, the physiological processes can be said to be stationary; therefore, here we will apply the method of time averaging (i.e., the use of the property of ergodicity.

Let us consider in greater detail the problem of processing the data obtained in an orbital flight. Since the reception time in different revolutions is not the same, the obtained data are selected samplings. These selections are random to a certain extent since they depend on the orbital projection of the spacecraft in the z ne of coverage of the receiving station and on the propagation conditions of the .io waves. As it is known, the most important property which the selected samplings should possess is its maximum reflection of all trends of the general sampling [209]. The question arises of to what extent the state of an organism in the period of information transmission to Earth reflects its state during all the remaining time in a given revolution. The field of statistics has a special numerical exponent which characterizes the degree of distinction between the selective and general sampling. This exponent is the mean error (m), which indicates how much the selective mean differs from the mean in a very large number of observations (general sampling). As a result of processing the telemetry data in orbital phases, basically insignificant mean errors were obtained, which points out the high reliability of the obtained selective means.

In statistical processing of numerical data, the following exponents were usually calculated: the arithmetic mean value (M), the standard deviation (σ), and the difference between the maximum and minimum values of each exponent (X_{mx}, X_{mn}).

For a clarification of the authenticity of the distinction between two means (in different revolutions) the coefficient t was determined:

$$t = \frac{M_1 - M_2}{\sqrt{m_1^2 + M_2^2}}.$$

Attempts also were made to calculate the self- and inter-correlation relationships, and also to extrapolate the data by the application of the method of least squares [122]. However, these more complicated mathematical methods of treatment require automation. The primary statistical and mathematical treatment of telemetry information is basically concerned with preparing the data for further scientific analysis. Indeed, many statistical exponents can have a concrete physiological significance. For instance, the variation factor [V] to some extent evidently reflects the level of nerve control of the vegetative functions [112, 33]. Determination of the authenticity of distinctions between mean values in different revolutions gives the physiologist mathematically substantiated facts. The development of methods for analyzing large volumes of nonuniform information, especially in reference to data obtained in a space flight, is a complicated task.

It is already absolutely clear that intense research on mathematical methods for evaluating each physiological parameter is necessary. A preliminary check of these methods in a large number of laboratory experiments and in the clinic will be of importance in this case.

The tediousness and ineffectiveness of manually processing large volumes of telemetry information brought about the appearance of a large number of proposals for the automation of this process. It is possible to isolate two trends of similar efforts:

a) automation of information readout (measurement); b) automation of processing the results of measurements.

With regard to the readout of information from different carriers (paper, film, and so forth), there is extensive literature [297], and it is not a complicated problem for nonintegrated recordings. Telemetry recordings, as a rule, are integrated, i.e., they are superimposed, forming intersecting lines, which complicates their automatic readout and requires manual assistance. At present these problems are being successfully solved. However, the most effective approach to recording is on magnetic tape, which can be directly introduced into a digital computer. Regarding the statistical and mathematical processing of data after manual measurement, punch-card and digital computers are now being used extensively.

The obtainment of a definite sum of digital indices which characterize the dynamics of physiological processes in the course of a flight experiment is only an initial, preparatory stage for a scientific evaluation of the results of the flight experiment. A thorough comparison of these data with each other and with the remaining flight data (microclimate of cabin, physical conditions of flight, radio-television data, operation of spacecraft systems, etc.) is the second stage of the scientific evaluation of telemetry data, as a result of which a judgement can be made about the reactions of the astronaut to the actions of a large number factors of space flight. Finally, the third and concluding stage of evaluation consists of clarifying the mechanisms and geneisis of the observed reactions and determining ways of further investigation, including investigations in the area of physiological methods and physiological measuring systems.

C H A P T E R 4

DESIGN PRINCIPLES OF PHYSIOLOGICAL MEASUREMENT AND INFORMATION SYSTEMS FOR USE ON LONG-TERM, LONG-RANGE SPACE FLIGHTS

The development of space research brought to life various projects which anticipate an essential increase of the duration and distance of flights. The task of this chapter is to discuss the main design principles of physiological measurement and information systems of spacecraft of the nearest future on the basis of numerous publications. Special attention is given here to a consideration of the methods of medical monitoring and the methods of medical investigation. The differentiated approach to each of these groups of methods, depending upon the tasks and conditions of the flight, in the final result, also composes a more expressed specific character of future physiological measurements in space.

Main Trends in the Refinement of Physiological Measurement Systems for Spacecraft

Flight experiments with animals and the multi-day flights of the "Vostoks" made it possible to gain rich experience in physiological measurement under the conditions of outer space. This experience has been summarised in a number of publications [6, 81, 289] and ways of further improving physiological measurement and information systems for spacecraft have been based on it. As already mentioned, the main purpose of the physiological measurments on the "Vostoks" was to provide flight safety and conduct reliable medical monitoring. The collection of scientific information on the influence of flight factors on an organism in this sense was an additional problem. Therefore, the physiological measurement system was constructed on the basis of the following principles:

1) all sensors and electrodes should be on the astronaut's body during the entire flight; 2) the transmission of physiological information from the sensors and

electrodes on the astronaut to the on-board equipment is carried but through wires, i.e., a special cable which connects the spacesuit to the seat; 3) the on-board medical equipment is controlled automatically from a program device or from Earth; 4) most of the data is recorded in the period of direct communication between the spacecraft and the ground points; 5) all physiological information is recorded in the form of oscillograms subject to subsequent interpretation and analysis.

The fulfillment of these principles was stipulated by the design features of the on-board equipment and the information collection system, as well as by the organization of the operational medical monitoring in the course of flight. However, in the multi-day flights definite tendencies were revealed, the development of which with the increase of the duration of flight will lead to a complete reconsideration of the entire system. Thus, the gradual expansion of the range of physiological measurements from flight to flight by means of installaing new instruments on board, changing the assignment of channels, and transmitting several parameters on one channel is absolutely obvious. It is absolutely clear that the tendency to increase the number of research methods will be subsequently retained. This is indicated by the publication of various proposals for programs of physiological measurements in space flight. Some programs offer up to 10 and more methods [512, 662, 756]. It is quite possible that even more detailed investigations of astronauts in flight will be demanded. However, this will lead to literally "weighing-down" the astronaut [illegible] electrodes and sensors if the principles of their constant position on the [illegible]ronaut's body during the entire flight are maintained. There are two opinions [illegible] this matter. Some authors consider the problems of microminiaturization of sensors and electrodes in order to make them "inconspicuous" to the astronaut and to ensure prolonged functioning without discomfort [413, 572]. Others consider it feasible to keep only a minimum of sensors and electrodes on the astronaut's body to obtain information which characterizes the state of his basic physiological functions and efficiency [669]. The remaining sensors should be employed only for the purpose of obtaining prognastic information [586, 601]. Some specially mention methods necessary for monitoring and investigation in flight [378].

In 1961 R. M. Bayevskiy and O. G. Gazenko proposed two independent measuring systems for long-term and long-range flights: a medical monitoring system and a medical research system [81].

The first is intended for ensuring space flight safety by means of operational monitoring of the most important physiological indices. To do this, a definite minimum of sensors and electrodes must continuously be on the astronaut and the system

must be ready to transmit information to Earth or inform the crew at any moment. This, in the words of Edmund [413], is the so-called "police surveillance" of the astronaut or the SOS service.

The second system is intended for more detailed medical investigations which are conducted for dispensary observation or collection of scientific information. Here there should be employed a system of detachable sensors and electrodes which would provide considerably more extensive and diverse physiological information than in the medical monitoring system. These sensors and electrodes can be independently attached by the astronauts at various moments of flight by instructions from Earth or according to a special program. On board there can be reserve sets of sensors as well as sets of sensors for various purposes (for instance, for planned and unplanned investigations). A similar approach to the construction of physiological measuring systems immediately expands the methodologic capabilities of the physiologists working in the field of space medicine and permits the application of methods under conditions of space flight which would be senseless to use in another approach.

In the flight of V. F. Bykovskiy and V. V. Tereshkova, where a large number of physiological measurements was made during the 3-5 day flight, the volume of physiological information proceeding to Earth could not be completely processed in the course of the flight, and for medical monitoring it was sufficient to observe a comparatively small number of the most important indices. This confirms the expediency of the differential approach to physiological measurements in space flight and the development of independent systems of medical monitoring and medical investigations. A change in the working and living conditions of the astronauts in a prolonged flight, the size of the living and working compartments, the composition of the on-board systems, and the possibilities of transmitting information to Earth (a sharp decrease in carrying capacity of the channels) will lead to an essential change in the requirements of the physiological measurement system. Among these requirements are the following:

a) the necessity of releasing the astronaut from constantly wearing most of the sensors and electrodes;

b) the necessity of releasing the astronaut from constant wire communications with the on-board equipment;

c) making it possible to record physiological data under "rest" conditions of the astronaut, when he is not communicating with Earth and not operating the spacecraft

equipment, i.e., in the period between of telemetry transmissions;

d) providing for the possibility of manual control of the medical equipment and active participation in carrying out the investigations;

e) the solution of the problem of "compression" of the biomedical data transmitted to Earth by eliminating excess information for data transmission on channels with sharply limited carrying capacities;

f) providing for automatic signaling to Earth and the crew in case of the appearance of conditions dangerous for life and health.

In the realization of these requirements we encounter the necessity of introducing new elements and units into future physiological measurement and information systems on spacecraft.

The provision for medical monitoring under conditions of free movement of the astronaut inside the spacecraft cabin involves the application of a radio link for transmitting information from the electrodes and sensors on the astronaut's body to the on-board equipment. Similar arrangements are called dynamic telemetry systems, and in space medicine are known as "minor" telemetry (in distinction from "major" telemetry, "spacecraft-to-Earth").

The development of a medical research system will make it possible to "unload" the astronaut of a large number of sensors and electrodes on his body. Most of them will be independently attached by the astronaut for the time of the investigation. .is will demand his active participation in the medical investigation: manual art-stop operation of the equipment, installation and removal of the sensors, and erformance of functional tests on a strict time schedule.

The realization of investigations in the period between telemetry communications will become possible only if the spacecraft has powerful memory units or digital computers (LBM) [TsVM] on board. The necessity of an on-board digital computer is also dictated by the task of "compressing" the medical information for its transmission to Earth through channels of limited capacity, for automatic signaling of dangerous situations, issuing recommendations, and also for solving many other problems of astronautics.

Later we shall present data on investigations devoted the search the most rational ways of creating certain new elements of physiological measurement and information systems: intracabin radio links, medical investigation systems, and devices for automatic processing of physiological information. These elements, together with the ones already considered, are the objects of a qualitatively new

physiological measurement and information system. The structure of this system is represented in Fig. 23. As can be seen, the system is characterized by a large number of various direct and reverse, afferent and efferent, communications. A physician on Earth can obtain information during a communication period or from a memory unit directly from the astronaut in the form of an oscillogram or a special on-board digital computer in the form of digits and code combinations. The astronaut controls the communications equipment and the medical research unit, and obtains information from Earth as well as from the special digital computer. Owing to the application of the special

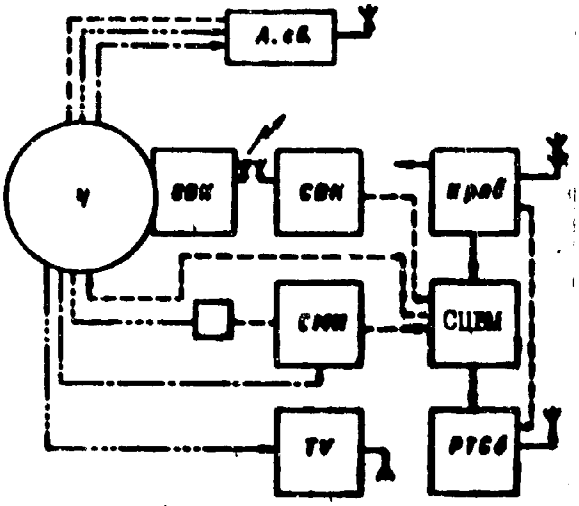

Fig. 23. Block diagram of on-board section of a physiological measurement and information system used for long-term and long-range space flights and distance. (Ч) [M] — man; (СМК) [MMS] — medical monitoring system; (СМИ) [MRS] — medical research system; TV — television; (Асв) [CE] — communications equipment; (Кр.пб) [CR] — command receiver; (РТСб) [OBTE] — on-board telemetry system; (СЦВМ) [SDC] — special digital computer.

digital computer, operational medical monitoring with recommendations made to the astronaut can be accomplished practically without delay, and problems of diagnostics and prognosis can be solved on Earth directly in the course of flight in periods from several minutes to several hours. Thus, an increase of the duration and distance of flights will lead to a further increase in the diagnostic effectiveness of the physiological measurement and information system at the expense of making it more complicated and introducing new elements into it.

Intracabin Dynamic Telemetry as a Basis for Medical Monitoring Systems

At present, the system of sensors and electrodes on an astronaut is connected to the measuring and amplifying devices on board the spacecraft by means of a special cable. This cable to a known degree limits the mobility of the astronaut, as if "attaching him" to the biotelemetry equipment on board. During free "floating" in the "Vostok" cabin, the astronauts were forced to disconnect the cable connecting them to the on-board equipment and, thus, in this period of time physiological information did not enter the measurement system.

An increase of the duration and range of space flights will lead to a radical change in the design of living quarters of spacecraft. An increase in crew strength

and the necessity of prolonged flight will lead to the organization of appropriate "space" living, parts of which at present are difficult to predict. However, it is clear that an astronaut will move freely through the sections of the spacecraft and will not be wired to the on-board equipment. At the same time, in each space flight, and especially those on new routes, there will remain the danger of unexpected effects (meteoric rains, cosmic radiation, and other, still unknown factors), and also the huge dependence of the crew on the conditions of the internal atmosphere of the craft. Therefore, there will be demanded periodic and, in certain phases of flight, continuous medical monitoring of crew members. The various repair operations to a craft in space obviously will also be done under medical control.

Thus, it is necessary to develop biotelemetry systems which will ensure the recording of the most important physiological parameters under the conditions of free movement of man.

The solution to this problem will require the transmission of information from man to the on-board equipment through a radio channel, which will lead to the creation of intracabin dynamic telemetry systems. Here there arise both technical and medical problems which are closely interrelated. The basic requirements of a similar intracabin system consist of the following:

1) the equipment placed on the astronaut must have minimum weight and dimensions with maximum time of continuous operation without replacing supply sources;

2) there must be stable reception of signals in any relative position of the astronaut and receiving antennas inside the cabin or compartments of the spacecraft;

3) the system of electrodes and sensors on the astronaut must not interfere with his activity and must not cause discomfort in a prolonged flight;

4) there must be qualitative recording of basic physiological functions under conditions of vigorous activity of the astronaut.

Systems of "minor" telemetry must be multichannel since reliable medical monitory requires simultaneous recording of several physiological parameters. The minimum number of parameters is determined from two circumstances: the possibility of providing sufficiently qualitative recording of a parameter under conditions of active behavior of the subject and its diagnostic value. We can cite many physiological parameters whose recording is theoretically necessary and expedient for medical monitoring: electroencephalography (delta-waves in syncopal states), sphygmography (low pulse rate during collapse), arterial oscillography (pressure drop during shock), oxyhemography (decrease in oxyhemoglobin saturation of blood during

hypoxia), and others. However, practically at the present time on the contemporary level of technology none of these methods can be used in the medical monitoring system on a spacecraft. On the other hand, there are many physiological parameters which can be successfully recorded during vigorous activity under conditions of free movement. These include pulse rate and EKG [40, 184, 216, 261, 314, 346, 377, 504, 505, 777), electromyogram [98, 226], body temperature [97, 314], and pulmonary ventilation [40, 184, 216, 262, 346].

At present we can cite only a tentative set of physiological methods which satisfy both conditions (the possibility of qualitative recording and the diagnostic value). Table 7 presents data on the methods and measured parameters which can be recommended in the design of medical monitoring systems for spacecraft.

Table 7. Physiological Methods for Medical Monitoring Under Conditions of Space Flight

Method	What is measured	Limits of measurement	Accuracy of measurement, % of measured magnitude
Electrocardiography	Pulse rate	20-300 per minute	±5
Pneumography	Respiratory rate	6-120 per minute	±5
Skin thermometry	Skin temperature	20-40°	±2
Actography	Motor activity	0-300 movements per minute	±10
Measurement of galvanic skin reflex	Electrical resistance of skin	500-100,000 ohms	±5
Pericardial ballistocardiography (seismocardiography)	Mechanical work of heart	5-20 mm/sec^2	±5
Recording of conditioned motor responses	Latent period of conditioned response	0.1-2 sec	±1.0

The table also shows the limits and accuracy of measurements. These data must be considered in the development of minor telemetry systems as well as when designing on-board systems of connected to the intracabin radio hookup (on-board telemetry system, memory units, computer units, etc.).

Multichannel systems of dynamic telemetry can be designed according to two principles: with channel multiplexing in the transmitter and transmission of all parameters on one carrier frequency with appropriate separation of channels at the receiving end; with autonomous transmission and reception of information for each parameter.

Systems with information multiplexing can be built on the basis of time or frequency separation, and also by means of combined transmission of several (distinguished by frequency spectra) parameters on one channel.

Brief descriptions are given below of experimental systems of dynamic telemetry which were created for the purpose of practical verification of the different design principles of equipment for medical monitoring.

Telemetry instrument with frequency separation of channels is designed for simultaneous transmission of four parameters [40]. The instrument has channels for transmission of three types of information: continuous rapidly-changing signals in a limited frequency spectrum (for instance, EKG transmission for monitoring pulse rate) constant level and slowly-changing stresses (for instance, skin resistance, body temperature), and signals of the form "yes — no" (contact sensors).

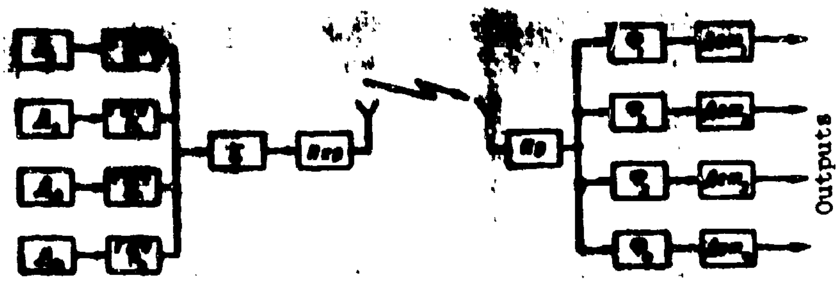

Fig. 24. Block diagram of biotelemetry system with frequency separation of channels. Д — sensors; ГПЧ — subcarrier-frequency oscillators; Σ — adder; Пер — transmitter; Пр — receivers; Ф — filters; Дем — detectors.

A block diagram of a telemetry link is given in Fig. 24. Amplified signals from the electrodes and sensors are amplitude-modulated by the subcarrier-frequency oscillator, the total signal of which in turn frequency-modulates the carrier-frequency oscillator-radio transmitter (AM-FM system). At the output of the receiver of the frequency-modulated signals, the subcarrier frequencies are separated by filters and then, by means of amplitude detection, voltages are obtained which are proportional to the measured parameters. The given system was tested under laboratory and clinical conditions. Pulse rate (electrocardiogram) was recorded by means of a chest harness with electrodes attached in the fifth intercostal space on the left and on the right along the central armpit line (DS lead), contact respiration and movement sensors mounted on a belt, and thermistors stitched to a strap system. A transmitter and antenna in the form of a conductor approximately 1-m long were placed on the subject. Recording was performed under conditions of vigorous activity of the subject at a distance of several meters from the receiving antenna. The weight

Fig. 25. Telemetry system with frequency separation of channels. пер — transmitter; прм — receiver.

of all the equipment on the test subject, including supply sources designed for continuous operation for several days, does not exceed 1 kg. Figure 25 shows a photograph of the transmitter and receiver of the described system.

Combined transmission of two parameters on one channel was carried out with the aid of a КРП-2 [KRP-2] instrument which was developed by the Sverdlovsk biotelemetry group [216]. The instrument was modified with respect to dimensions and power consumption. By doing this, it was possible to achieve continuous operation of the instrument for twenty-four hours without replacing the supply source with a total weight of no more than 500 g (A. A. Bessonov). Data was recorded by a (4ПФД-7) [4PFD-7] and a simple UHF-receiver with a superregenerative circuit (P. Ignatenko). The instrument was tested by I. P. Neumyvakin. After connecting the EKG electrodes (in the DS lead) to the amplifier input and the contact respiration sensor to the multivibrator circuit (function converter), recordings were obtained which clearly noted the pulse and respiratory rates. Stable recordings were obtained at distances up to 50 m (Fig. 26).

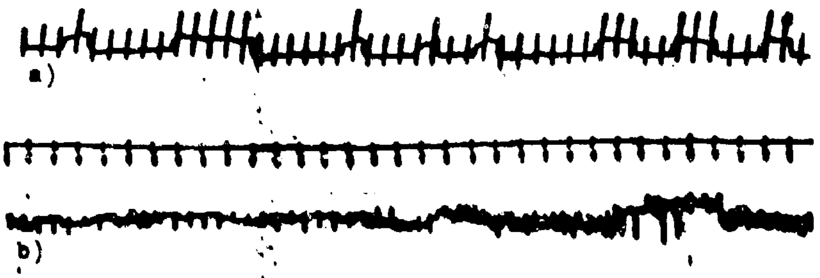

Fig. 26. Combined recording of pulse and respiration obtained with the aid of a modified KRP-2 instrument at distances of 10 (a) and 60 (b) m.

Time-division multiplexing for rapidly varying signals with small transmitter size and weight is technically difficult to accomplish. However, for prolonged

observation of the physiological systems of the organism under conditions of stationary steady-state regimes (for instance, in a multi-day orbital flight), consecutive recording of parameters is permissible and expedient. The frequency of channel switching is then selected within the limits defined by the medical monitoring tasks. Consequently, it is then possible to use long-period systems with time separation.

We formulated the requirements for two types of such systems: with automatic and manual switching.

The system with automatic switching is intended for the consecutive transmission of three parameters, e.g., electrocardiogram, seismocardiogram, and respiratory rate (contact sensor), or other parameters with analogous frequency spectra. An electronic switching circuit is employed, and a transmitter with crystal control and amplitude modulation is used [184]. Its range is 8-10 m (operation was conducted on radio frequencies on the order of 200 kc). The weight of the transmitter is approximately 800 g. The frequency of automatic switching in an assembled prototype of the instrument was selected within the limits of 5-6 per minute. R. V. Unzhin employed a timing mechanism for switching two parameters [254].

The method of manual switching was applied in a single-channel multipurpose telemetry system which made according to our specifications at Sverdlovsk for the consecutive transmission of data during prolonged observation [303]. The instrument was assembled on the basis of a (P8K-1) [REK-1] system [216]. Crystal frequency control is used. The range of operating frequencies is 35-45 Mc. The system is FM-FM. The amplifier has an input impedance of several kilohms and a sensitivity of the order of 50 μv per mv of receiver output voltage during operation at distances of 10-20 m.*

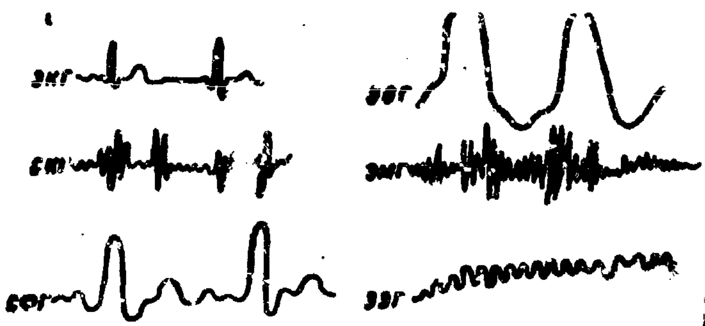

Fig. 27. Samples of recordings of seismocardiogram, electrocardiogram, electroencephalogram, electromyogram, sphygmogram and electrooculogram with the aid of a single-channel multipurpose telemetry system with manual switching.

The instrument has 10 inputs and a manual switch (the 11th position is used to supply a control signal of 100 μv to the amplifier input). The frequency band of the amplifier is from 0.5 to 40 cps. The amplitude difference between input signals of

*The system uses a standard (APC) [ARS] receiver.

the various sensors is removed by the application of appropriate voltage dividers.

Figure 27 illustrates samples of recordings of physiological parameters that were obtained with the aid of the above-described multipurpose system. Figure 28 shows the transmitter, receiver, and EKG recorder.

Autonomous transmission of physiological data on divided telemetry channels with their separate reception has definite technical advantages and disadvantages. The physiologist will be interested on the low probability of channel interference, and also in the known autonomy of tuning of the receiver with respect to each recorded parameter.

A system with autonomous transmission can be easily constructed by means of the structural connection of several single-channel systems, e.g., ones similar to the above-described multipurpose instrument. Crystal frequency control has an important value here in providing stability of recordings.

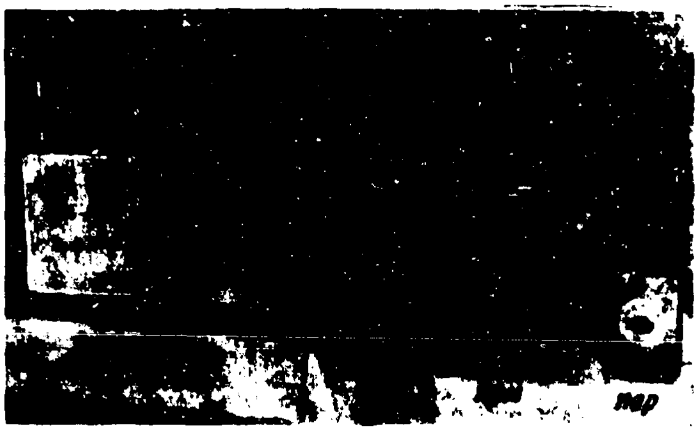

Fig. 28. Multipurpose single-channel bio-telemetry system with manual switching. пер — transmitter; прм — receiver; Р — EKG recorder.

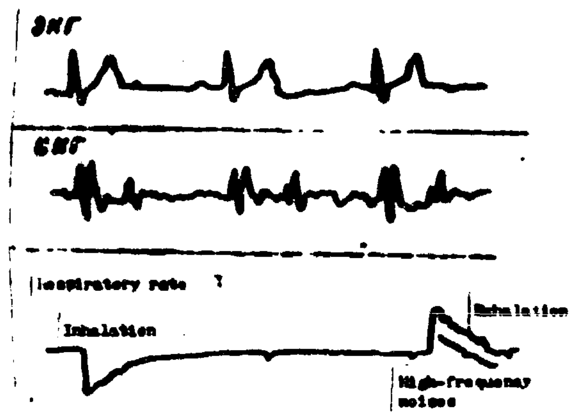

Fig. 29. Samples of recordings obtained with the aid of a biotelemetric system with autonomous channels. ЭКГ — electrocardiogram; СКГ — seismocardiogram.

A special experimental instrument was constructed for the transmission of three parameters (V. R. Freydel', I. P. Sazonov, et al). This instrument is designed to record electrocardiograms, seismocardiograms, and respiratory rate (contact sensor) or signals with a similar frequency spectrum. Frequency control both in the receiver and in the transmitter is crystal. The frequency range is 5-10 Mc. The transmission range is up to 10 m. The weight of the transmitter is 300 g (without supply sources). Samples of recordings obtained with the described system are represented in Fig. 29.

Power supplies and design features of certain systems. All the enumerated

telemetry devices with respect to the principle of their power supply refer to systems with self-contained power supplies. Usually be series, as we know, have a finite service life and require periodic replacement or recharging. Therefore, the idea of the possibility of dropping our concern for power supplies of telemetry transmitters on astronauts is very tempting. This is important also from the point of view of ensuring reliability of medical monitoring since unlimited recording of physiological functions will become possible under any conditions, even if the astronaut cannot, for one reason on another, replace or recharge the power supply of the transmitter. Besides self-contained power supplies, there are two more methods of obtaining power for a telemetry device that is located on an astronaut. The first method is an external supply which gets its power from a specially created artificial electromagnetic field. The second method is the conversion of biological processes into electrical energy.

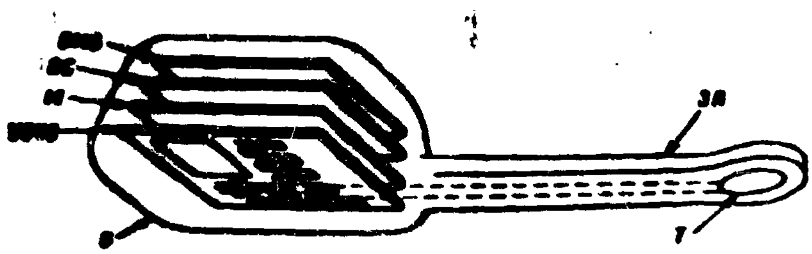

Fig. 30. Transmitter-sensor developed by Lear Inc. (1960). [illegible] — power-rectifier receiver; ПС — signal transmitter; М — modulator; УСЧВ — sensor amplifier; О — transmitter-sensor envelope; ЗП — protective covering of sensor; Т — thermistor.

Power supplies that receive energy from an electromagnetic field are used in a great deal of American developments. For instance, Lear Inc. developed a 12-channel telemetry system with an inductive power supply. Each sensor is in the form of an independent transceiver. It consists of its own sensor, amplifier, generator, receiving loop, and rectifying circuit (Fig. 30). The transmitter-sensor has small dimensions and is placed directly on the subject's body. The on-board generator, which sets up an electromagnetic field to supply the transmitter-sensors, operates consecutively on 12 frequencies. Each frequency ($f - f_{12}$) corresponds to a specific sensor (Fig. 31); f_0 is the frequency of the receiving loop. Transmission and reception of physiological information is done on one frequency. Thus, the described system operates as if on the principle of time-division multiplexing, since the transmitter-sensors are actuated by "commands" from the on-board generator in a definite time sequence. The switching frequency can be selected in a range of a few

seconds for series recording of physiological data, as well as in a range of microseconds, which ensures practically parallel recording of the investigated functions.

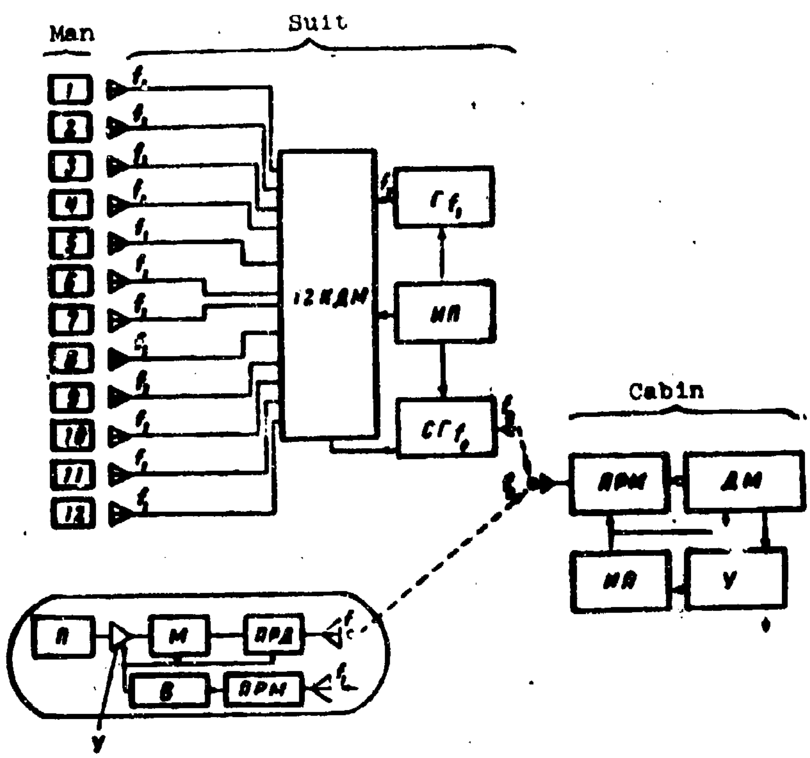

Fig. 31. Block diagram of 12-channel biotelemetry system with inductive power supply developed by Lear Inc (1960). П – converter (sensor) У – amplifier; В – rectifier; М – modulator; ПРД – transmitter; ПРМ – receiver; ДМ – demodulator; ИП – power source; Г – generator; СГ – synchronizing generator; КДМ – 12-channel generator-demodulator; 1-12 – transmitter-sensors placed on man; f_1 – frequency of power generator for feeding transmitter-sensors; f_0 – operating frequency of transmitter-sensors.

In our opinion the inductive method of supplying power, which requires considerable radio emission outputs, is not very suitable for investigations of a human being in a spacecraft. First, it does not exclude the unfavorable effect of an electromagnetic field on a living organism. Secondly, the creation of an electromagnetic field requires very considerable power consumption. Efficiency is then extremely low. An inductive power supply system is applicable only for investigations with animals (biological indication), and even then mainly for implanted systems under the condition of periodic recharging of the storage batteries located inside the organism.

The method of biological power supply is promising, i.e., the use of the energy of the actual subject of investigation. First of all we should mention the well-known

"soldier-motor,"* i.e., an electric generator that is actuated by means of turning a handle or pedals. Such "biological" sources of energy were included in the equipment of certain armies in the period of the Second World War.

It is quite natural to plan for the use of human muscular force for "generating" a definite amount of electric power on a spacecraft. There already exist corresponding calculations with respect to the "economy" of muscles as a source of electrical energy [578]. Thus, for instance, it would be quite reasonable to simultaneously use physical exercises and special loads on a craft for recharging the on-board power sources. However, the problem of providing energy for the biotelemetry instruments placed on an astronaut is very complicated. It requires the solution of at least two problems:

find effective methods of converting biological processes into electrical energy;

develop highly economical amplifying and transmitting radio circuits with respect to power consumption.

Table 8. Feasibilities of Using Biological Energy as the Power Supply for Telemetry Devices

Biological process	Method of conversion	Publications on experimental tests of given type of converter
Muscular activity (motor activity)	Piezoelements implanted in muscle mass	Long [606]
The same	Seismic motion transducer with piezoelectric converter	Long [814]
Blood circulation	Piezoelement implanted in wall of aorta	Myers [642]
Bioelectric processes	Direct tapping of electrical energy	Reynolds [672]
Oxidation of organic matter	Biochemical fuel cells	Wolff [780] Konikoff [574
Respiration	Chest movement	–
Metabolism (heat regulation)	Temperature difference at various portions of the body	–
Speech	Body and air vibrations	Cited in [192]

Table 8 presents data on the possible ways of obtaining electrical energy by means of the conversion of various processes of vital activity.

Figure 31 represents the circuit of Long's seismic transducer for converting motion into electrical energy [814]. The transducer was used for supplying power to a miniature telemetry transmitter.

*Usually a foot-operated generator [Tr. Ed. note].

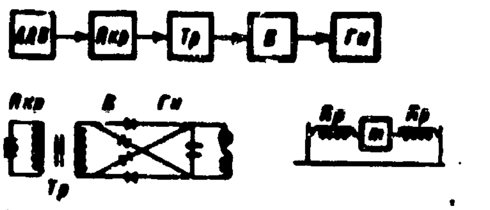

Fig. 32. Conversion of biological energy (motion) in electrical energy. ДДВ — motion transducer; m — weight attached to two springs (see circuit, bottom right); Пкр — piezocrystal connected to weight; Тр — transformer; В — rectifier; $Г_{н}$ — oscillator. The electrical circuit is shown at bottom left (Long, 1962).

The transducer-transmitter consists of a seismic weight secured by two springs and connected to piezoelements. The electronic circuit includes a resonance transformer, diode rectifier with filter, and a tunnel-diode high-frequency generator. A description of some other biological power-supply devices for implanted systems is given in the next chapter.

There is one more way of increasing the period of continuous operation of telemetric transmitters without replacing the power sources. This is done by increasing the operational economy of biotelemetry systems by means of improving the research procedures. We are thinking in terms of the reasonable selection of work cycles of a system, inasmuch as it is not always necessary to have continuous control. Thus, under conditions of prolonged orbital flight it is apparently quite permissible to periodically connect the medical monitoring system, e.g., for 5 minutes every hour. This gives a 12-fold gain in the power resource of the biotelemetry system, i.e., a self-contained power source designed for continuous operation for 3 days with such cyclical operation can ensure medical monitoring for 36 days. Start-stop operation of the biotelemetry transmitter can be done manually or automatically. In the last case it is most economic to use a timing mechanism; we can also use remote automatic switching by means of supplying a powerful radio signal which, by acting upon the receiving antenna and detector circuit, causes the relay of the power source to close. Control of the telemetric transmitter is possible also by means of biological signals (see the section in this book entitled "Biocontrol," Chapter 6).

Finally, we must mention the efforts in the field of so-called "magnetic telemetry" the pioneer of which in the USSR is B. V. Panin, who constructed a capsule for studying intentinal peristalsis in sheep.

B. V. Panin's capsule consists of an A-F oscillator with an RC circuit on a ferrite rod and a self-contained power source. The work of the oscillator can be detected with the aid of a loop antenna and a low-frequency amplifier at distances of several meters. By changing the inductance of the circuit by means of bringing the ferrite plate attached to the diaphragm of the capsule near to the ferrite rod, it is possible to record displacements of up to 0.05 mm.

In cooperation with B. V. Panin, we developed a system for respiration recording on the basis of this principle. It is possible to use both the principle of the contact pickup and the principle of the change in perimeter of the chest. In the first case the respiratory process controls the starting and stopping of the oscillator; in the second case the ferrite plate is the movable element of a conventional respiration transducer which is placed on the chest. The low-frequency amplifier with the look antenna has an output at a loudspeaker (for audio monitoring) and at a recording instrument (EKG) or at a vectorcardioscope for visual observation of respiration signals.

A very important problem in the construction of "minor" telemetry devices is the miniaturization of equipment, which is closely related to power-supply economy. At present the spacing of elements in special equipment is up to 10 per cm^3; however, in the very near future it will be possible to construct systems with spacing of up to 1000 elements per cm^3 [565].

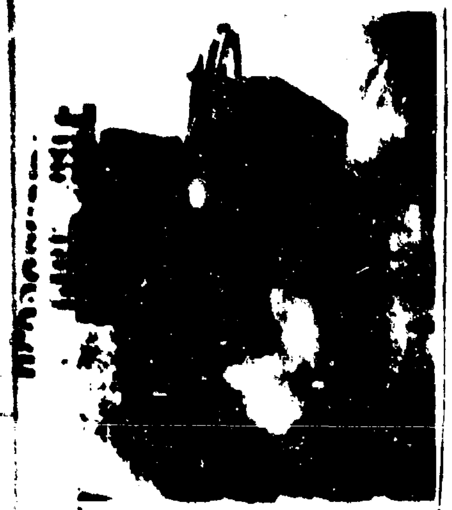

Fig. 33. Miniature transmitter placed on the head of a cat (Fischler et al, 1961).

The miniaturization of biomedical equipment is being worked on by a large number of foreign firms: Martin [442], Guldon [773], Douglas [572], Boeing [413], North Am. Inc [467] and others [446, 572]. Various miniature biotelemetric systems have been developed for installation on a human or an animal (Fig. 33) [24, 242, 279, 332, 389, 413, 781, 621, 714, 742, 718, 793, 364]. One of these systems is being used for rescue operations [810].

A three-channel system for transmitting pulse, respiration, and body temperature with a weight of approximately 150 g, was described by Marko [620]. A 600-gram, 200-microwatt, 12-channel system with an electronic transmitter was reported on at the instrumentation automation conference in Los Angeles in 1961 [403]. One of latest developments is a tunnel-diode transmitter with an input sensitivity of 5 μv. Its weight is 3 g and its dimensions are 1.2 × 1.2 × 0.8 cm [751]. An interesting report was given on a system for telemetric EKG transmission made in the form of a fountain pen [806].

Many researchers consider the microminiaturization of equipment to be one of the basic conditions for the development of biomedical technique in astronautics [446, 701].

Methodological problems of "minor" telemetry also are of importance. Prolonged medical monitoring under conditions of free movement is possible only in the complete absence of discomfort. An astronaut should not feel any inconveniences from the equipment or sensors placed on him. The sensors and electrodes should be natural parts of the astronaut's clothing, such as a watch, belt, or shirt. Therefore, research in the field of dynamic biotelemetry also should be conducted towards the development of systems for attaching electrodes and sensors, e.g., sensors built into the clothing.

Systems of dynamic ("minor") telemetry are very important to the development of space biology not only with respect to providing reliable medical monitoring in flight, but also for solving a number of research problems. After all, it is known tha physiological reactions at rest considerably differ from reactions during the performance of work.

Sports medicine, the physiology of work, and clinics are beginning to extensively use biotelemetry for studying physiological states in dynamics. It is clear that the investigation of a human being under dynamic conditions for a long time under the influence of unusual factors (weightlessness, cosmic radiation, rotation) is of extreme scientific and practical interest.

It is possible to assume that systems of "minor" telemetry will become an inalienable part of spacecraft in the very near future and, naturally, the problems of their development and improvement are of much interest to physicians and engineers working in the field of space biology.

Design Principles of Medical Research Systems

An increase of the duration of flight will demand the liberation of the astronaut from a large portion of the electrodes and sensors which he could constantly wear in brief flights. At the same time, prolonged space flight, at least at the present time, requires not only the organization of reliable medical monitoring, but also rather extensive and inclusive medical research.

Such research should obviously have two goals: to promote the collection of scientific information on the physiological reactions of living organisms to the sustained action of the complex of factors of space flight, including weightlessness (a research problem); to ensure medical monitoring of the state of astronauts and possibly earlier manifestation of minimum deviations in their vital activity (a diagnostic problem).

It is clear that the solution of these problems requires the use of a large number of various physiological methods and an extensive telemetry program. As was shown above, the contradiction between the necessity of decreasing the number of sensors on an astronaut and the necessity of increasing the number of methods employed for medical research was solved by means of developing an independent medical research system. This system is distinguished, first of all, by its detachable sensors.

Detachable sensors must satisfy the following requirements: they must be convenient and simple and must not cause difficulties in independent installation by an astronaut under conditions of space flight; they must ensure the obtainment of standard and high-quality recordings; they must not cause discomfort during investigation.

The introduction of detachable sensors makes the astronaut an active participant in biomedical research. This imposes definite obligations and responsibilities on him. The fact is that even the simplest system for attaching electrodes and sensors will require the astronaut to perform specific working operations, i.e., purposeful activity. With a sufficient level of efficiency, the installation of sensor will not cause any difficulties; however, a lowering of efficiency can result in the inaccurate installation of electrodes and sensors or the impossibility of their installation in general. From the point of view of a medical research program, this is certainly a disadvantage. However, from the point of view of medical monitoring, . › impossibility of the installation of sensors is easily interpreted as an essential ›vering in efficiency and, thus, a timely decision with respect to the state of the astronaut can be made.

The activity of an astronaut in a medical research program is not exhausted by the installation of detachable sensors. The obtainment of vitally important scientific information requires more than the recording of physiological functions only during complete rest or during the usual work of an astronaut in communications and control. The performance of functional tests is an absolutely obligatory requirement of clinical physiology in the realization of purposeful medical research [162]. The simplest functional tests, such as shutting the eyes, holding the breath, and apportioned physical loading, can be easily introduced into the physiological measurement program on a spacecraft and performed by an astronaut. In addition, the research program can be essentially expanded by means of switching the measuring channels. Indeed, the performance the functional test of holding the breath requires a detailed study of the functional shifts in the cardiovascular and respiratory systems. Conversely, phychological tests should be accompanied by more thorough

monitoring of functions which characterize the state of the central nervous system and analyzers. This plan can employ the principle of using the same measurement channels for recording different physiological functions. Narrow specialization of measurement channels would lead to the fact that in certain periods of time certain channels would be idle and their total number would be very considerable. Switching can be accomplished automatically or manually by the astronaut himself. In this case, either sensors requiring hookups to channels with identical characteristics are switched, or elements of the amplifying-measuring system are switched, as a result of which the channel characteristics are changed. An example of the first type is the switching of seismocardiogram and sphygmogram sensors on one EKG channel. An example of the second type is the switching of electromyogram and electroencephalogram sensors on one channel, which requires a change in the frequency response of the channel. The switching method is convenient in the respect that the necessary sensors can be placed on the body simultaneously and then hooked up to the recording channels according to the specified program.

For the purpose of simplifying the methods of collecting medical information, it is expedient to consider the possibility of series or parallel use of the same electrodes and sensors for recording different physiological parameters. For instance, electrodes for electroencephalogram recording also can serve for intracranial electroplethysmogram recording. An EKG electrode can be mounted on the chest in such a way so that a miniature thermistor can be built into it for recording skin temperature. It is possible to foresee three types of combined systems for collecting physiological information:

a) systems with series recording of different parameters from the same sensors;

b) systems with parallel recording of different parameters from the same, structurally common, electrodes and sensors;

c) systems with parallel recording of different parameters from the same, electrically common, electrodes and sensors [636].

A good example of a combined system of the third type is a sensor in the form of a tube containing carbon powder or a piezoelement mounted around the perimeter of the chest which provides simultaneous pneumogram and volume kinetocardiogram recording (pulse vibrations of chest perimeter). The realization of this type of recording requires two amplifiers with frequency responses of 0-5 and 15-50 cps.

It is also possible to use one channel with a standard characteristic, whereby a kinetocardiogram is recorded while the breath is held (see Fig. 79).

Thus, the program of astronaut actions in the period of medical research includes the installation of electrodes and sensors, the switching of measuring channels, and the performance of assigned functional tests. It is very important that the astronaut's activity in the program of medical research be strictly limited in time. This is related to the following circumstances:

1. A strict time schedule of astronaut activity is a unique functional test for accuracy and correctness in executing the research program. Deviations in the time of executing the entire program or parts of it from the standard obtained as a result of ground laboratory tests with the astronaut have an important diagnostic value.

2. The time of the communication period of the spacecraft telemetering system with Earth is strictly limited. Therefore, the time of investigation should not be greater than the duration of a communication period. Indeed, the use of telemetry systems with data storage and accelerated reproduction of information makes it possible to avoid this difficult to some extent; however, the final volume of information transmitted from the craft to Earth always will be limited by the specific channel capacity.

By using an on-board computer for data processing to Earth, not only can oscillograms themselves be transmitted, but also the results of medical research in the form of numbers, graphs, and final conclusions. The channel capacity for transmitting medical research data can then be decreased by hundreds of times. The presence in on-board computer also provides control of the research program and gives the astronaut the necessary instructions.

As can be seen, physiological measurements in future space flights will essentially differ from the measurements that are presently conducted. In the first "Vostok" flights the task of medical monitoring was considered to be of prime importance. It was required that the physiological information from the spacecraft proceed independently of the desire and state of the astronaut. The physiological measuring system was turned on automatically and operated during the entire time of telemetric communication without any participation of the astronaut. The "Vostok" flights made it possible to obtain proof of the retention of sufficiently high efficiency of a human being following a many-hour period of weightlessness. Thus, there are no obstacles placed before the construction of more rational and effective physiological measurement and information systems in which the role of the astronaut will not be passive, but active. The first experience of programmed collection of research information, as it is known, was conducted during the flight of the "Voskhod."

Physician-astronaut B. B. Yegorov recorded a number of parameters for himself and his companions with the aid of detachable sensors and electrodes and special research equipment which was manually controlled.

Programming of astronaut actions in the course of physiological investigations involves the solution of the following problems:

1) selection of functional tests that are adequate for the conditions of flight in a spacecraft;

2)determination of the sequence of astronaut actions and the order of measurments;

3) development of a time schedule of research;

4) training of astronauts and collection of reference data.

It is absolutely natural for physicians to wish to obtain maximum information on the state of an astronaut. However, when considering the peculiarities of medical research, there always exists the alternative of either obtaining general data on the state of the various systems of the organism or detailed data on the state of a certain specific physiological function. It is clear that the creation of a "universal" program is a considerably more complicated matter than the development of so-called particular or specialized programs.

A universal program or, to be more exact, a general-medical program, is analogous to the primary medical examination which a physician makes, for example, in polyclinical admission. His task includes a determination of the general state of health of the patient and the necessity of rendering him specialized help. A medical specialist, such as a neuropathologist, examines his patient according to a purposeful program for manifesting specific deviations related to the state of the nervous system. Similar to this, the specialized programs of medical research in flight must be purposeful. It would be incorrect, however, to consider that specialized programs must be performed by an astronaut only according to special instructions in case of the appearance of any deviations. After all, in a dispensary examination, absolutely healthy people are checked by specialists. This provides a more substantial basis for conducting planned examinations of an astronaut in flight.

In the development of appropriate programs it is necessary to carefully select the research methods and functional tests. Functional tests for independent performance by astronauts must be simple, should not cause unpleasant sensations, and must ensure the obtainment of a clear shift in the state of several physiological

functions. The tests should be apportioned and standardized, i.e., they should be performed in the same manner in all cases. One of the measuring channels should be used for monitoring the performance of functional tests. This does not require the creation of special devices. For instance, during physical loading, the motions of the subject will be reflected on the recordings of respiration, electroencephalogram, and other parameters. The tests should correspond to the conditions of flight. Thus, for the purpose of physical loading, considering the volume of the spacecraft cabin, neither squatting nor running can be done. Val'sal'vo's test is difficult to measure out. The finger-nose test is difficult to objectively evaluate (it is necessary to employ special television equipment). Besides the selection of well-known standard clinical functional tests which correspond to the requirements of flight experimentation, many tests can be modified in reference to the conditions of space flight.

As already was indicated, within the limits of each research program there is established a clear sequence of astronaut actions. Work is done on a strict time schedule and the correctness of its performance is its own type of functional test for efficiency. The time schedule can be set up by two methods:

1) in the form of an initial reference signal followed by the performance of all operations "by hours" (the astronaut himself makes sure that every one of his actions is strictly performed at the specified time);

2) in the form of a sequence of command signals which indicate the character the operation to be executed (these signals can be sent from Earth or from an on-board program device [timer] or digital computer). Similar program devices have already been employed in certain laboratories [126, 224, 630].

An experimental check of a system of detachable sensors and research programs was conducted in several special experiments of 10-20 days in length, and also under clinical and polyclinical conditions. Different variations of general-medical and specialized programs were developed. An example of a general-medical program is given in Table 9. One of the specialized programs for investigating efficiency is considered in Chapter 9. The same chapter more specifically examines the research program of physiological measurements on the "Voskhod." Figure 34 illustrates samples of recordings obtained in the process of executing a general-medical program. These recordings well illustrate the polygraphic and functional approach to medical research.

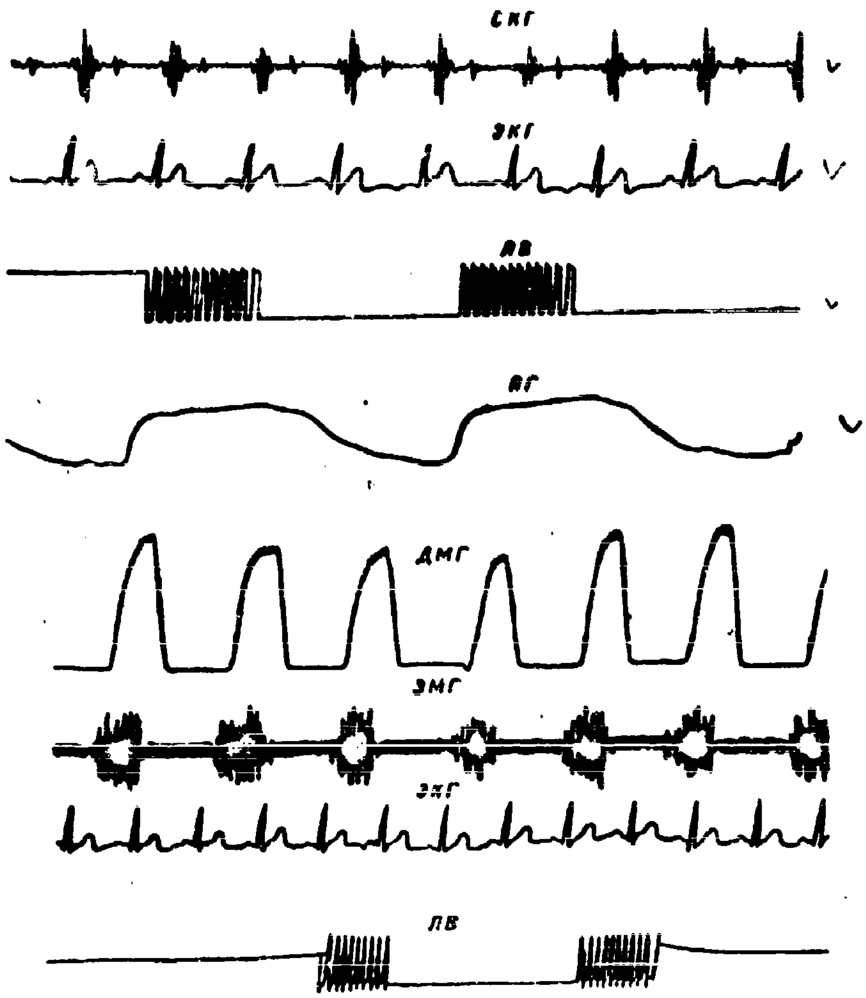

Fig. 34. Samples of recordings obtained in the process of executing a general medical program (upper four recordings — at rest; lower — during work of a dynamograph). ЭКГ — electrocardiogram; ПГ — pneumogram; СКГ — seismocardiogram; ЛВ — pulmonary ventilation; ЭМГ — electromyogram; ДМГ — dynamogram.

It is important to point out that the proper and thorough interpretation of the results obtained in the process of programmed research requires data of the same standard research conducted under laboratory conditions. Therefore, a necessary condition of the introduction of programmed research into the practice of space flights is the preliminary training and instruction of astronauts and the extensive collection of reference data.

Further expansion of the program of physiological measurements on spacecraft, and the use of newer research methods cannot involve an increase in the number of telemetry channels. First of all, it is economically unprofitable; secondly, it is not necessary

to simultaneously record data which are not compared with each in the process of analysis.

Table 9. A Variation of a General-Medical Research Program

Command	Subject's response	Time from beginning of recording, sec	Duration of recording (operation), sec	Recorded parameters
Attention	Sits calmly without tension	0	20	ЭЭГ, ПГ, СКГ, АД, ЛВ, ЭКГ
Close eyes	Close eyes	20	20	ЭЭГ, АД, ЭКГ, ЛВ
Open eyes	Open eyes	40	20	АД, ККГ, СКГ, ЭКГ
Hold breath	Inhales, holds breath for 10 sec, and then exhales for 10 sec	60	30	ККГ, СКГ, ЛВ, ЭКГ
Dynamography	Work with dynamograph at a rate of once per second	90	60	ЭМГ, ДМГ, ЛВ, ЭКГ
Attention	Sit calmly without tension	150	90	ККГ, ЛВ, ЭКГ, СКГ
End	Remove sensors and electrodes	240	—	—

Table 10. Typical Medical Research Program on a Spacecraft.*

General-medical research program	Specialized research programs			
	cardiovascular system	external respiration	efficiency	vestibular apparatus
ЭКГ	ЭКГ	ПТГ	ЭКГ	ЭКГ
ПГ	СФГ—ККГ	CO_2	УДР	УДР
СКГ	СКГ	O_2	ЭМГ	ЭПГ череп
ЭЭГ	ЭПГ груд.	ЭПГ груд.	ЭЭГ	ЭЭГ
ДМГ	ОГГ	ОГГ	ДМГ	КГР
АД	АД	ТВ	АД	АД
ЛВ	ФКГ	ЛВ	ЛВ	ЭОГ
ТТ	ПКГ	γ	П	П

*ПКГ — pulmocardiography; ПТГ — pneumotachography; CO_2 and O_2 — carbon dioxide and oxygen content in exhaled air; ОГГ — oxyhemogram; ТВ — temperature difference between inhaled and exhaled air; γ — humidity difference between inhaled and exhaled air; ЭПГ груд. — pectoral electroplethysmogram; ЭПГ череп. — cranial electroplethysmogram.

We have already mentioned the expediency of the consecutive switching of several sensors on one measuring channel according to an appropriate program.

Table 10 illustrates a typical in-flight medical research program which includes 25 physiological methods. Eight telemetry channels (it is possible also to construct

a program for four channels) should be used to record data. Five research programs are proposed, including one general-medical and four specialized. Practically all of these physiological methods, with the exception of methods on the program for studying external respiration, have already been employed under laboratory conditions for preflight and postflight examination of astronauts, and consequently, their application on board a spacecraft is a thing of the near future.

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CHAPTER 5

ON-BOARD AUTOMATIC PHYSIOLOGICAL INFORMATION PROCESSING SYSTEMS

The expansion of the range of research tasks and the necessity of increasing the reliability of medical monitoring are accompanied by an increase in the amount of information subject to transmission from a spacecraft to Earth. At the same time, an increase of the duration and range of flight will lead to a considerable limitation on the capabilities of information transmission.

Thus, there appears an important problem — to transmit maximum information with the use of telemetry channels of limited capacity [35, 196]. A solution to this problem is possible only with the aid of the facilities of computer technology, e.g., analog or digital computers. Therefore, one of the important elements of future physiological measurement and information systems will be the on-board automatic physiological data processing system (CAO) [ADP]. However, the functional capabilities of an ADP system are not exhausted only by the "compression" of information for more effective use of telemetry channels. An ADP system also can be used to solve other problems, such as a quick evaluation of the state of an astronaut in flight and a significant reduction in the periods of scientific data analysis. Indeed, these problems also can be successfully solved with the aid of ground computers connected to the receiving telemetry station. Thus, the main problem is to increase the effectiveness of the telemetry links inasmuch as at the present time it is impossible to provide power for a radio system that is sufficient for the transmission of a wide frequency band for long space trips. Therefore, the considerable limitation in the capacity of the telemetry links makes it absolutely necessary to install an on-board

ADP systems in such cases. There are also other considerations in favor of on-board ADP systems.

First of all, we should mention the possibility of informing the crew of the spacecraft about its condition and the issuance of recommendations in case of the appearance of dangerous situations. Similar signaling will be carried out without the participation of a medical staff on Earth, which is very essential for the flight phases in which there is no communication with Earth.

On multiseat spacecraft, where the crew will probably include a physician [635], the ADP system also will be able to perform the role of a "machine-adviser" or be used for solving medical diagnostic problems (see below).

With the direct introduction of information from man to the ADP system in the appropriate way, processed and generalized physiological information can be used for the following purposes: for regulating the operation of life-support systems (especially in closed ecologic systems); for controlling emergency rescue systems; for biocontrol of the spacecraft in the event of physical incapability of the pilot to accomplish complicated tasks (for instance, the use of muscle biopotentials for control during the action of large G-loads).

The necessity of automatic processing of medical information on board a spacecraft was exhibited long before the first manned space flight took place. One of first designs of an on-board ADP system was published by McLenan in 1959 [616].

McLenan's system is designed to send one of seven signals to a telemetry channel which carry information on the physiological state of an astronaut. The principle of action of the system consists of using a scanning device for examining all information proceeding from the astronaut with subsequent binary selection through each channel and shaping of a conditional signal (code) with the aid of simple "And" and "Not" logical circuits. The system is designed to process information on the efficiency and physiological state of an astronaut. Efficiency is determined in the form of the "highest" or "lowest" level of functioning. From the physiological parameters, the following are considered: eye movements, muscular activity, and heart activity. To differentiate between sleep and unconsciousness, the author proposes the application of a stimulus signal that is sent by radio which, in the case of sleep, should ensure a transition to a higher level of functioning. The system is designed to transmit one three-bit binary digit (from 0 to 7) by telemetry, which is the code of the astronaut's state. However, the proposed system is too general and cannot be completely used for medical research as the problems of medical in-flight monitoring.

In 1961 there appeared a publication concerning a ground system for automatic processing of data coming from a spacecraft [375, 376]. The system was modeled under clinical conditions with the use of a universal digital computer. Recently in the foreign press there have appeared publications concerning the development of miniature on-board logical systems for processing medical data [467, 554] However, specific information concerning the method of introducing the information, algorithms, or technical operating principles of these systems is not given.

The first Soviet publication which substantiates the need for on-board ADP systems and explains certain principles of their construction if the work by O. G. Gazenko and R. M. Bayevskiy [81]. Subsequently these questions were considered more specifically in many Soviet articles [289, 33, 36, 5, 9, 282]. At the present time there has already been a significant amount of experience gained on the subject of multi-day manned space flights and the problems of designing on-board ADP systems have become considerably clearer and more intelligible. The United States has developed an on-board digital computer that weighs 5 kilograms, takes up 2 dm^3 of space, and has a power consumption of 20 watts [799].

On-board systems for automatic processing of physiological information do not differ in principle from the various systems proposed for the automation of physiological measurements and the diagnostic process in laboratories and clinics. The presently existing devices and systems for automatic processing of physiological data can be divided into three groups:

devices for automatic processing of separate physiological parameters, e.g., cardiotachometers, integrators, correlographs, and so forth [175, 185, 25, 657, 208]; systems for automatic evaluation of a situation by a group of physiological parameters, e.g., electronic logical systems, devices which warn of the existance of dangerous situations [34, 7, 58, 695, 794, 812]; instruments for automatic diagnosis, i.e., "diagnostic machines" [16, 68, 563, 590, 591].

All of these groups are closely interrelated and are data processing systems with a gradually constructed algorithm.

Algorithms

The questions of the development of algorithms occupy a central position among the problems of automatic data processing. The work "algorithm" was derived from the name of the Persian mathematician, Al-Khuwārizmi, who lived in the 9th century [197, 251]. An algorithm is an exact instruction on a sequence of actions which are

necessary to solve specific types of problems. The application of computers for automatic data processing involves the use of specific algorithms, on the basis of which a program is composed. Programming belongs to the sphere of digital computer specialists. A general (initial) algorithm should be developed by specialists of the field of science whose problems are to be solved with the aid of a digital computer. It is naturally what these initial algorithms are composed in terms which are peculiar to the given area of study.

We introduced the concept of the "diagnostic algorithm," which implies any algorithm that involves the realization of a diagnostic process. Inasmuch as practically any procedure of interpretation, analysis, and evaluation of one or many physiological parameters is involved with diagnostics, the diagnostic algorithm is the basic concept of a physiological measurement and information system. A description of the diagnostic algorithm includes all operations which pertain to the conversion of information, beginning with its collection and terminating with the shaping of signals for feedback circuits. The principle of construction of each specific algorithm depends on the problem which it must solve. We shall briefly consider the principles of construction of three groups of algorithms in accordance with the three groups of devices and systems for automatic processing of physiological data which we considered earlier.

1. Algorithms for the solution of problems related to the analysis of separate physiological parameters can be constructed on the basis of the following principles: determination of the numerical value of one of the indices, e.g., determination of pulse rate by means of an electrocardiogram, cardiotachometer, or cardiointervalograph [130, 175, 419, 462, 489, 559, 657]; logical evaluation of a selected index, e.g., as this is done in the "Rhythm-1" instrument (V. S. Gurfinkel' and M. L Tsetlin) [1267]; determination of a series of indices, e.g., the waves and intervals of an electrocardiogram and their relationships [668, 440, 489, 369, 370]; statistical analysis of the indices of a given parameter [155, 384, 485, 487]; special mathematical analysis of the indices of a given parameter, e.g., determination of the autocorrelation function of the spectral density, and so forth [23, 62, 211, 435, 456, 730, 733, 734, 771, 697].

It is natural that a technical solution depends on the complexity of the selected algorithm. In some cases it is sufficient to have a very simple counting circuit, while in others it is necessary to use a computer. Although the application of a digital computer for processing all of one parameter is not very expedient, many

scientific investigations on the use of a digital computer in medicine are devoted precisely to this question. Thus, we know of work on the application of digital computer for processing electrocardiograms [371, 622, 729], electroencephalograms [146, 639, 646, 674], phonocardiograms [453], kinetocardiograms [307, 308], and others.

2. Algorithms for evaluating a group of physiological parameters are intended for the determination of symptom complexes. Here, much depends on the selection of the parameters and the indices subject to analysis. Algorithms of a similar type must consider the physician's logic. The principles of constructing these algorithms have not yet been sufficiently studied. Therefore it is possible to name only some of the possible appraoches to the solution of this problem: determination of a symptom or syndrome according to one or several pathologic deviations or by the sum of untypical deviations, but characteristic for their specific combination, (matrix principle); comparison of the directivity of shifts observed simultaneously on the part of several parameters (for instance, pulse increases and arterial pressure drops); probability logic of evaluating deviations; evaluation of the degree of correlation of indices; application of special mathematical methods which ensure the best approach to effective identification of a specific syndrome (the syndrome as an information form).

The realization of these algorithms is possible with the aid of analog computers as well as with digital computers.

3. Algorithms of the diagnostic process are presently the subject of numerous investigations. There are several different views on this question. Thus, Lusted and Ledly [590] state that the most effective algorithm is the one based on the calculation of the conditional probabilities of separate symptoms in a disease complex. Tanimoto (749) devised a diagnosis for polycythemia on an IBM 704 digital computer on the basis of the matrix principle (symptoms-cases).

In the opinion of A. A. Vishnevskiy, N. L. Bykhovskiy, and I. I. Artobolevskiy [68], automation of the diagnostic process can be based on three logical processes: deterministic logic, probability logic, and phase interval logic. These processes, to the minds of the authors, well simulate the physician's logic with respect to differential diagnostics and selection of the most probable diagnosis from a series of possible ones. It should be mentioned, however, that the mathematical evaluation of even extremely simple diagnostic methods is very difficult. For instance, the same symptom can be determined in different diseases, but its significance in every case depends not only on the character of the disease, but also on with what other

symptoms it is combined.

Consequently, it is also necessary to consider the probability and correlation criteria and the logical relationships and mass of other criteria. Therefore, it is still impossible to discuss diagnostic algorithms in detail; however, work in this direction is extremely important and urgent [396, 563].

Going on to the consideration of work algorithms of on-board ADP systems, we must emphasize the wide range of possible approaches to this question. Therefore we will begin with an account of the simplest algorithms for processing individual physiological parameters (encoding) and will gradually go on to the more complicated algorithms.

When investigating the possibilities of transmitting a maximum amount of information through channels of limited capacity, we must first of all turn to the propositions of information theory, in particular to its sections which illuminate the methods of optimum encoding. Actual messages (including physiological information) contain both useful and useless information. The latter pertains to the repetition of information or to information that is of no use for diagnostics from the point of view of the present status of science. Thus, when considering an electrocardiogram, we are dealing with a periodically and strictly repeating process (with the exception of cases of extrapolation). If we extract only necessary (useful) information from message its transmission will require telemetry channels with up to a hundred times smaller capacity than for the transmission of the initial message. The presence of useless data in messages along with useful information is called redundancy in information theory [66]. The positive value of redundancy consists in the fact that it facilitates the identification of individual errors which accompany the transmission of messages and increases the noise immunity of transmission. Thus, the repetition of EKG cycles, even with a high noise level, makes it possible to consider the individual elements of the curve by comparing the neighboring cycles between one another. Thus, one of methods of effective encoding of physiological information can be based on the elimination of redundancy [35].

The principle of code forming should be selected by taking into account the most important (to the physician) criteria contained in the given message. Thus, in EKG processing, approximately 10 different indices are computed, such as PQ, QRS, SP, A_P, and A_T. The frequency of measurement of these indices is no more than one per minute. Consequently, in a 20-minute recording it is necessary to determine

approximately 200 digital indices (during a 20-minute telemetry recording of an electrocardiogram approximately 0.5 million bits of information should be transmitted to Earth.) Let us imagine that all calculations are performed on board the spacecraft and an EKG is not transmitted to Earth, but already calculated indices. What will be the gain in the sense of the capacity of the telemetry channel and the time of transmission? If a four-digit binary code is used for transmission, a 200-character message will contain approximately 1000 bits, i.e., 500 times less than the original electrocardiogram. Consequently, a channel with a 500 bits/sec capacity will take only a total of about 2 seconds to transmit this message instead of 20 minutes, and a channel with a capacity of only about 1 bit/sec can be used in a transmission time of 20 minutes (instead of 500 bits/sec).

But the application of an ADP system ensures, besides a gain in channel capacity and, transmission time, a higher operational efficiency of medical monitoring of an astronaut, since the information obtained on Earth does not require interpretation and can be evaluated directly in the course of flight.

A further decrease in the number of messages subject to transmission from a spacecraft to Earth can be attained by means of constructing a code which would reflect not the digital values of the indices, but their relationship to a definite class of values. The simplest symbol in this case (for instance, "0") is used to code the range of normal (the most frequently encountered) values of the index.

More complicated symbols (1, 2, 3) are used to code the pathologic values of an index. For instance, for PO, the values are (0.12-0.20) = 0, (0.21-0.25) = 1, and (0.26 and higher) = 2.

A similar method of encoding can be said to be statistical, inasmuch as it considers the probability of the appearance of certain signals.

Statistical encoding is more effective than nonstatistical encoding [417, 647]. However, the statistical distribution of values cannot always be taken into account for medical information.

An effective code can be constructed on the principle of indicating the deviations of a given parameter beyond the limits of its specified range (Fig. 35). The simplest two-position code (0 and 1) indicates only the presence or absence of deviations, while the three-position code (+, –, H) indicates the sign of the deviation. The most practical is the four-position code, which makes it possible to determine, in addition to the pathological values, the transition values, which is important for a prognosis. Codes also can be constructed on the basis of statistical and

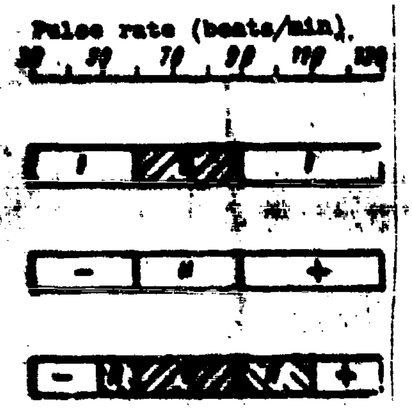

Fig. 35. Methods of encoding deviations of physiological parameters (see text).

probability indices. Thus we have considered the version of an algorithm for the anlaysis of an electrocardiogram which is based on the calculation of specific indices. This type of algorithm can be realized by a digital computer as well as by an analog computer.

Now we shall consider an algorithm that is directed towards the identification of a symptom, a syndrome and, finally, the determination of a diagnosis. Here it is necessary to consider the character of the physician's logic. Let us consider how the diagnostic process is performed by a physician. We can tentatively isolate three stages of this process.

1. Collection of information about the patient by means of questioning, physical examination, and laboratory and clinical analyses.

2. Evaluation of the information collected from the point of view of isolating signs which are symptoms of a disease. In other words, all data are distributed into two groups (norm-pathology).

3. Comparison of the sum of isolated symptoms with symptom complexes known to physician and the establishment of an identity, i.e., determination of the symptom complexes existing in the patient (and then, a diagnosis by the combination of symptom complexes).

These three stages reflect the physician's logic (in the general sense). However, in the realization of the described actions, the physician does not only use logical rules, but also definite, specific information in his memory. Even the sequence of logical operations required for diagnosis should be first "recorded" in his memory. Then his memory should record the program of activity for each stage of the diagnostic process. Finally, the physician should memorize the data which he has taken as the standard, with which he compares the information obtained as a result of examination.

Consequently, the physician's memory, along with the physician's logic, composes an important element of the theory of constructing an ADP system for physiological information.

Already, in the realization of even extremely simple algorithms, we are encountering the necessity of recording the values of the norm in the memory of the logical

unit or computer, i.e., the limits of variation of each parameter, which are considered to be normal. But, as it is known, there do not exist rigid norms for the majority of physiological indices. For instance, a pulse of 120 beats per minute following moderate physical exercise (20 squats) is normal for an untrained person and pathological for an athlete.

The physiologic norm is a dynamic concept which is stipulated by the individual peculiarities, the degree of training, the conditions of examination, and so forth. Quantitative expressions are generally unknown for many important indices, and therefore there are no norms (for instance, the degree of facial pallor or perspiration during syncopal and precoma states). Special investigations of such indices and quantitative criteria for them are necessary. The most correct approach to the problem of norms in astronautics is the statistical processing of a large number of realizations of an investigated function in various conditions of laboratory tests, training sessions, and prelaunching periods. This ensures the obtainment of individualized, statistically reliable norm. For instance, after the realization of a number of manned space flights, we now can speak of the norms in the propelled flight of a spacecraft. These norms are calculated according to data obtained as a result of the analysis of telemetry information. Similar statistical norms can be used as the basis for programming future on-board ADP systems.

In addition to statistical norms, there also exist critical values of individual indices, which by themselves indicate evident trouble. For instance, a quickening of the pulse to 200 per minute is an extraordinary circumstance not only for a trained person, but also for an untrained one.

The concept which we developed concerning statistical norms and critical values corresponds to the conception of V. B. Malkin and his co-authors [103, 167] concerning two types of deviations: deviations of separate parameters from individual norms and deviations which characterize the extreme absolute values of parameters.

When making his diagnosis, the physician evaluates various symptoms differently: some higher, others lower. In other words, every symptom in a symptom complex has its own weight. If we compare the values of the symptoms of the drop in arterial pressure and the lowering of skin temperature during a collapse, the first symptom undoubtedly has a larger "weight" than the second. A decrease in the amplitude of the first tone of a phonocardiogram can have quite an insignificant "weight" in the same symptom complex. Calculation of the weight of separate symptoms can be performed

with the probability approach to the analysis and evaluation of information. The probability of each symptom complex is equal to the sum of probabilities of its component symptoms; on the other hand, the probability of a given symptom complex in the presence of a definite number of criteria further depends on other conditions (selection of control parameters, time and place of investigation, the individual characteristics of the subject, and others). Attempts have been made to determine a diagnosis on the basis of the Baez formula [58, 59], which was applied for calculating the probabilities of interdependent events. In a general case it is possible to say that each index has a definite probability of being normal or pathological, and each symptom characterizes one state or another with a definite probability. Therefore, the calculation of probabilities is an important operation of the algorithm, but medicine, unfortunately, and space medicine in particular, cannot yet express its experience in probability calculation.

A no less important role in the construction of diagnostic algorithms is played by the correlation indices between different physiological parameters [208].

All physiological parameters in an integral organism are interdependent. A pathological state of one of the systems of an organism immediately causes a deviation in the other systems; however, the factor that determines the influence of one system on another can vary depending upon the conditions, the individual characteristics, the severity of the disease, and so forth. The relationships between biological processes, symptoms, and physiological parameters can be direct, inverse, logarithmic, parabolic, and so forth. The mathematical analysis of pathological processes requires a study of the control curves of various functions and their interdependence [20, 197]. The calculation of correlation functions and correlation factors is one of the methods which helps us to clarify the interdependence of different physiological indices. With a very high correlation it is possible to determine the value of one index with respect to another, i.e., to optimize the diagnostic algorithm. For instance, we know of the possibility of determining pulse rate with respect to respiration (45) and the minute volume of the vital capacity of the lungs [490]. The correlation approach to evaluating physiological information makes it possible to decrease the number of control indices without impairing the quality of control.

Other mathematical methods (integration, differentiation, spectral analysis) also can essentially increase the quality of diagnostics; however, the practical application of the above-mentioned methods requires the collection of data and

special research work.

Computers

The construction of on-board ADP systems brings up some very complicated problems, which are related to the following: the conversion of analog signals into digital form or the separation of a specific portion of the most significant or the most important physiological indices in the given investigation; the mathematical and logical processing digital indices for obtaining generalized characteristics; the formation of conclusions, i.e., "diagnoses" (syndromes, symptoms), on the basis of the results of the preceding stages of automatic processing and the analysis of physiological information.

In accordance with these problems we can consider three trends of research in the area of developing on-board ADP systems which involve the technical realization of specific diagnostic algorithms.

Coders convert physiological information from analog form into a discrete form expressed by a specific code. The purpose of conversion is: a) to decrease the volume of information subject to transmission through telemetry channels; b) to present information in a form that is more convenient for subsequent analysis.

Let us first consider the method of effective encoding of the most high-frequency physiological parameters of an electromyogram and an electroencephalogram. We proposed this method in 1959 and realized it in the form of a working mockup of physiological equipment. The encoding principle consists in determining the frequency and amplitude characteristics of the process and shaping of signals which individually reflect these characteristics [196, 197, 204]. We developed a system for the transmission of four electromyogram recordings or four electroencephalogram recordings through one telemetry channel (Fig. 36).

The program for electromyogram encoding consisted of determining the frequency and amplitude of the signals per second and shaping two amplitude-modulated pulses corresponding to the values of the frequency and amplitude. To do this, we used a counter with a storage unit and an integrator with a storage unit. The storage units were capacitors. Each of the four channels, thus, had two storage units apiece. The entire system has 8 capacitor-storage units. The output device of the instrument is a commutator with an 8-element capacitative memory unit. The work cycle of the output device is equal to the storage time. In the beginning of a cycle the commutator simultaneously connects all the memory elements to the storage units and their levels

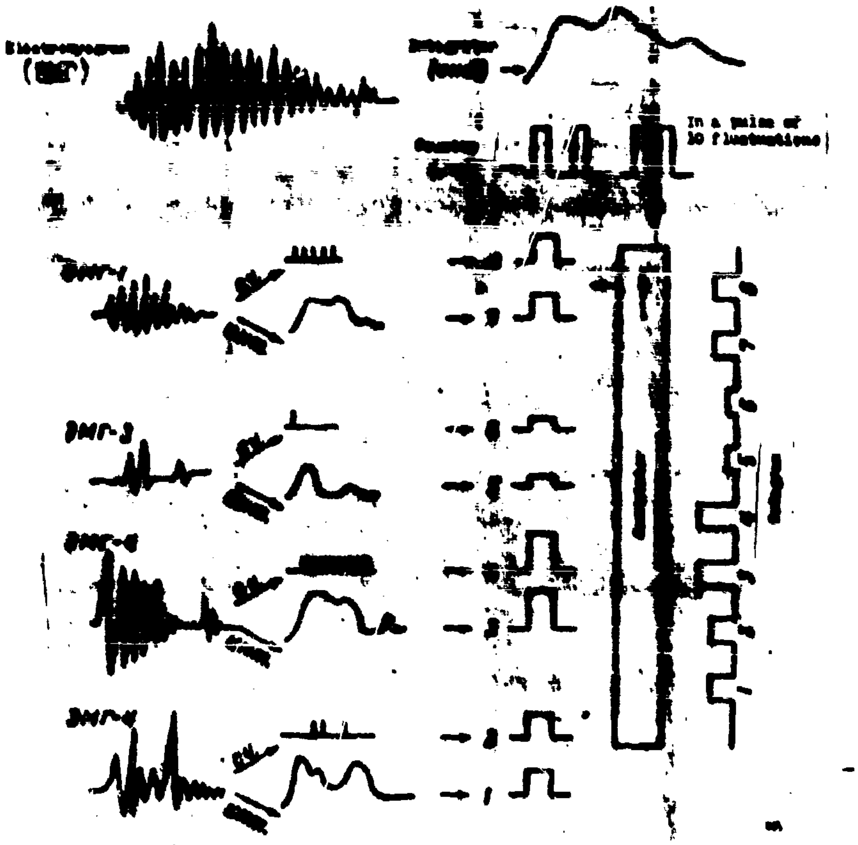

Fig. 36. Method for single-channel recording of data on the frequency and amplitude status of four electromyogram recordings.

are memorized. This operation takes approximately 0.05 sec. Then, simultaneously with the cutoff of the memory units, the storage units are cut to zero. After that, the commutator consecutively connects the memory elements to the recorder for the remaining time, which records 8 levels that reflect the frequency and amplitude of the muscle biocurrents in each of the four leads in the last second. After recording the information contained in the last memory element, a drop to zero is automatically performed and connection to the storage units again takes place.

The program for electroencephalogram encoding consisted of determining the integral values of the α-, β-, γ- and δ-frequencies and the total signal. Similar methods of analysis are extensively described in literature [111, 146]. Four narrow-band frequency filters and five storage-integrators were used. In all, the four channels had 20 storage-integrators (Fig. 37). The system for recording on one channel was analogous to the electromyographic arrangement. The commutation time was 2 sec. The storage time also was about two sec. Thus, the instrument performed simultaneous

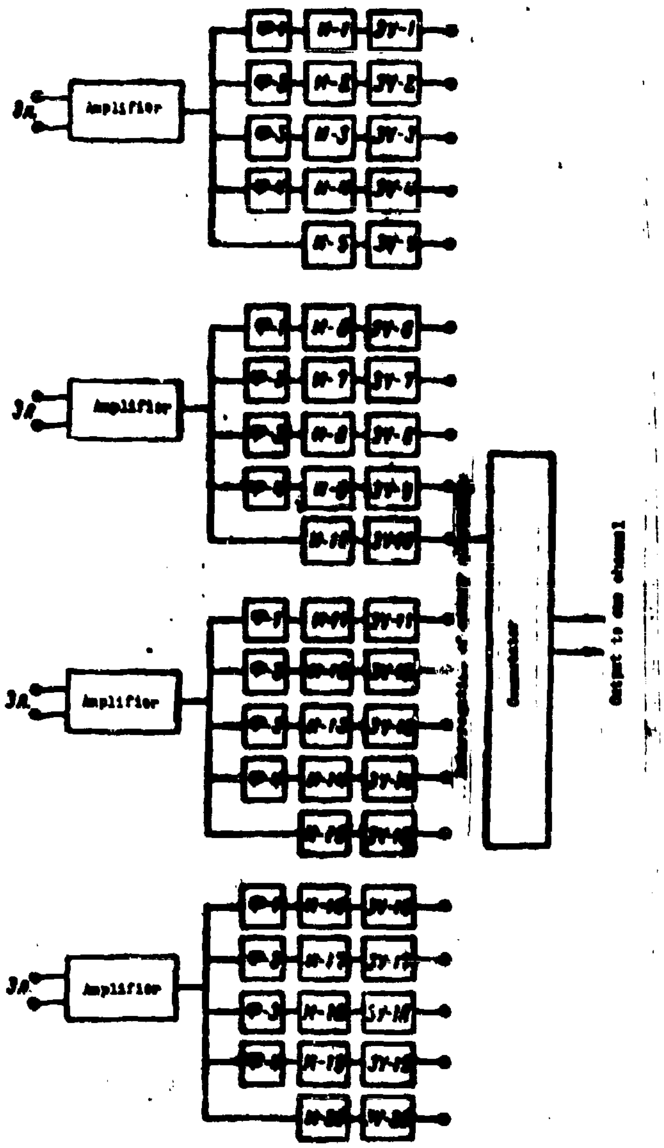

Fig. 37. Block diagram of instrument for single-channel recording of four electroencephalograms. ЭЛ — electrodes; Ф — filters; И — integrators; ЗУ — memory units.

automatic frequency analysis of two-second segments of four electroencephalogram leads (Fig. 38).

As can be seen, in both cases the principle of single-channel recording was applied to several biopotential leads. The same principle can be used for recording indices that are different in character.

In 1960 we built a mockup of a recompute-encode module [REM] (ПКБ) for single-channel recording of pulse and respiratory rate and intensity of movements. A block diagram of the instrument and a sample of a recording are shown in Fig. 39b. The data processing program consisted of determining the pulse and respiration rate with the aid of counters and the intensity of movements by means of integrating the signals from a potentiometer pickup. The circuit generated output pulses of different amplitude every 50 pulse beats, 25 respirations, and 20 movements. The outputs of three channels were connected with the aid of an adder to the recorder and each form of information was recorded in the form of a definite pulse magnitude. In the event of pulse coincidence, the pulse amplitudes were added together.

It is possible to carry out single-channel recording of other parameters in a similar manner.

The simplest form of single-channel recording was developed in reference to the "Signal" transmitter which was installed on the "Vostoks." If we change the duration of audio sendings which correspond to the pulse rate to the rhythm of respiration, we

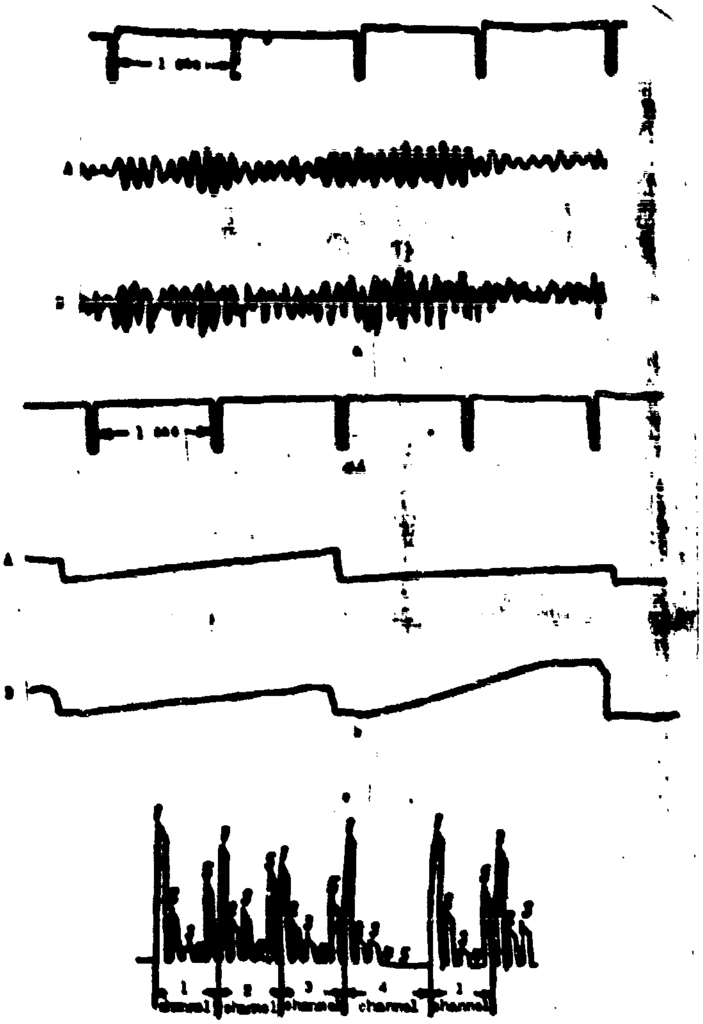

Fig. 38. Samples of recordings obtained with the aid of an instrument for single-channel recording of four electroencephalogram leads. a) oscillograms at output of alpha-frequency filter (A) and amplifier (Б); b) oscillograms at output of alpha-frequency integrators (A) and total signal (B); c) single-channel recording of four electroencephalogram leads. The first pulse reflects the energy of the total signal. The following four pulses reflect the energy of the α-, β-, γ-, and δ-frequencies, respectively. The data of four channels are consecutively commutated, i.e., a total of 20 pulses.

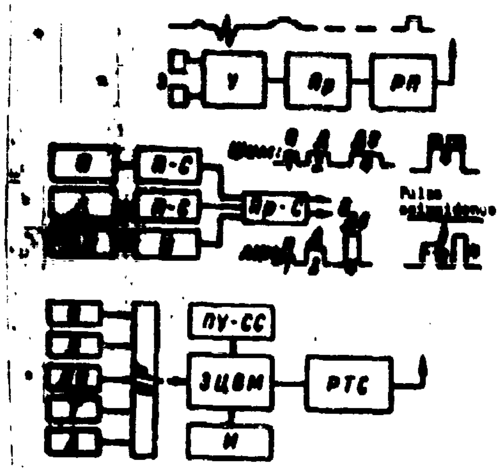

Fig. 39. Methods of encoding physiological information. a) pulse transmission by means of electrocardiophone through "Signal" transmitter; b) recompute-encode system for three parameters; c) encoding with digital computer; Э — electrodes; У — amplifier; Пр — converter; РП — radio transmitter; П — pulse; Д — respiration; Дв — motion; П-С — conversion circuit; И — integrator; Пр-С — converter-adder; В — output; АИМ — pulse-amplitude modulation; ШИМ — pulse-width modulation; ПУ-СС — recovery control panel; Т — temperature; А — cabin atmosphere; ЭЦВМ — digital computer; И — crew information; РТС — telemetry system.

can obtain additional information on the respiratory rate. The technical realization of this idea consists in controlling the duration of the pulse produced by a slave multivibrator with the aid of a contact respiration sensor (Fig. 40). The pulse length at inhalation amounts to 100-150 msec, and 200-300 msec at exhalation. A similar system was used for operational medical monitoring on the "Voskhod."

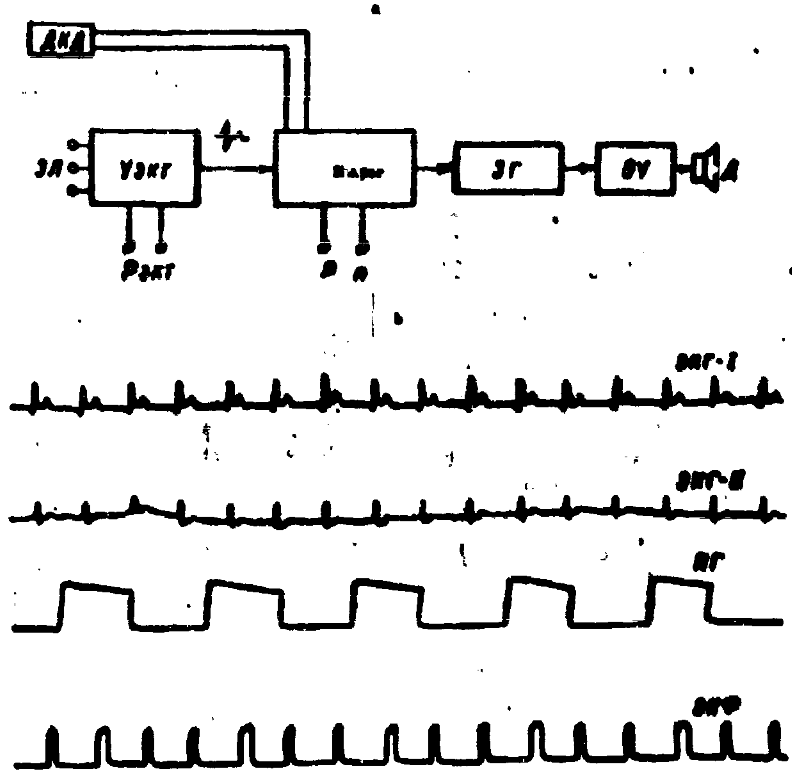

Fig. 40. Single channel recording of pulse and respiratory rate in reference to a "Signal" system. a) block diagram of system; ДКД – contact respiration sensor; ЭЛ – electrodes; $У_{ЭКГ}$ – electrocardiogram amplifier; $P_{ЭКГ}$ – output at electrocardiogram recorder; $P_{П}$ – output at pulse-rate recorder; ЗГ – audio-frequency oscillator; ОУ – terminal amplifier; Д – dynamic loudspeaker; b) sample of experimental recording (change of pulse duration through ЭКФ (EKP) channel in accordance with respiration); ЭКГ – electrocardiogram; ПГ – pneumogram; ЭКФ – electrocardiophone signals.

Automatic logical devices provide an evaluation of a set of parameters according to specified criteria. These devices work on a "rigid" program, which is determined by the construction of the instrument. Different forms of automatic logical devices are described in the bibliography [5, 34, 103, 199, 758, 812]. A distinctive feature of the devices considered below is the application of a diode matrix for realization of the diagnostic algorithm. The idea of employing a diode matrix belongs to author jointly with the B. A. Soshin [9, 34].

The algorithm for the operation of electronic logical devices can be represented in the general form of three consecutive operations: 1 – measurement of the monitored index during a specified interval of time (for instance, determination of the number of pulses in 10 sec or the average voltage level in the same interval of time);

2 – comparison of the values obtained with the specified limits of the norm and determination of the current state of each indice (for instance, in the form of symbols "N", "+", or "-" – depending upon whether the monitored index is in the specified range, is increased or decreased);

3 – comparison of the symbols obtained during the analysis of separate parameters, and shaping of a conditional code, i.e., the "diagnosis."

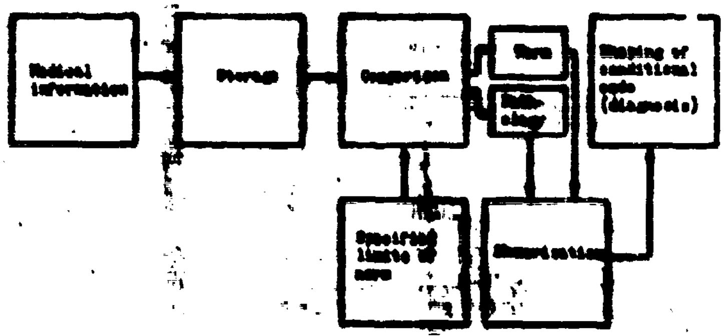

Fig. 41. Block diagram of diagnostic algorithm.

In accordance with the considered algorithm, Fig. 41 illustrates a block diagram of the operations executed by an automatic logical system.

Two mockups of logical systems working on the indicated principle were developed. The first one was constructed in cooperation with engineers V. Ya. Kostikov, A. P. Kalinovskiy, and B. A. Soshin. The system was designed for the analysis of the following indices: pulse rate [PR] (ЧП), respiratory rate [RR] (ЧД), body temperature [BT] (TT), conditioned motor response time [MR] (ДР), level of motor activity [M] (Д), electrical resistance of skin [ERS] (ЭСК), air temperature [AT] (ТВ), carbon dioxide content (CO_2), and oxygen content (O_2) in the surrounding atmosphere. A block diagram of the system is represented in Fig. 42. Analysis of information through channels PR, RR, and M was carried out with the aid of a discrete counting circuit on the basis of a binary counter controlled by a slave multivibrator. Counting was performed in 10-second intervals of time. The measured values were compared with the specified ones with the aid of a code register in which the norms were recorded. A comparison circuit controlled by flip-flops was used to analyze information on the remaining channels. A controlled matrix was used to shape conditional signals corresponding to specific combinations of deviations. A program of logical evaluation which was composed in reference to different forms of syncopes is represented in Table 11.

Table 11. Program for Electronic Logical System Operation

Code	Parameters								
	ЧП	ЧД	ТТ	ЗСК	ОР	Д	$СО_2$	$О_2$	ТВ
1	+	+	+	—	—	—	Н	Н	+
2	+	+	—	—	—	—	Н	—	Н
2	—	—	—	—	—	—	+	Н	Н
0	Н	Н	Н	Н	Н	Н	Н	Н	Н

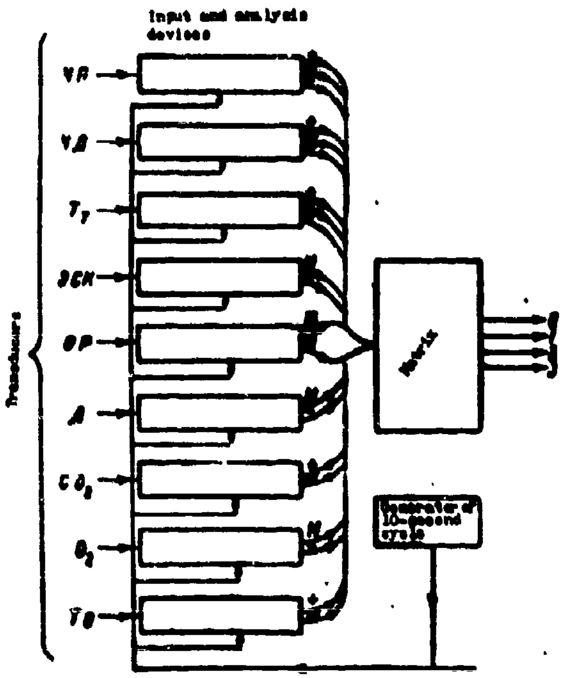

Fig. 42. Block diagram of automatic logical system (variation 1).

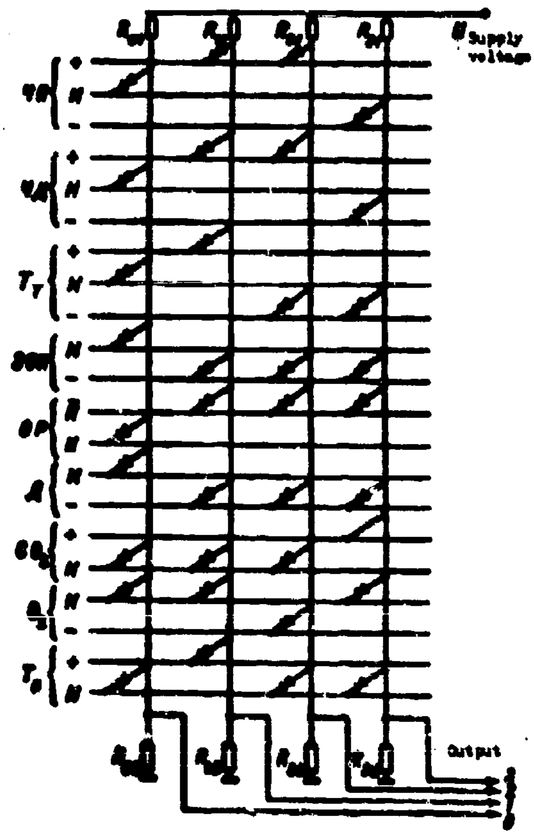

Fig. 43. Diagram of diode matrix programmed in accordance with Table 11 (see text).

Figure 43 illustrates a diagram of a diode matrix that was programmed in accordance with the table.

A second logical system was developed in cooperation with engineers Ye. A. Zil'bertil', V. M. Kruzenshtern, and V. G. Freydel' [34]. It was also designed for diagnosing syncopes. Figure 44 illustrates a block diagram of this system. Its basic units are: a) transducers for converting biological process into electrical signals; b) amplifying-measuring units; c) selection and memory circuits, which

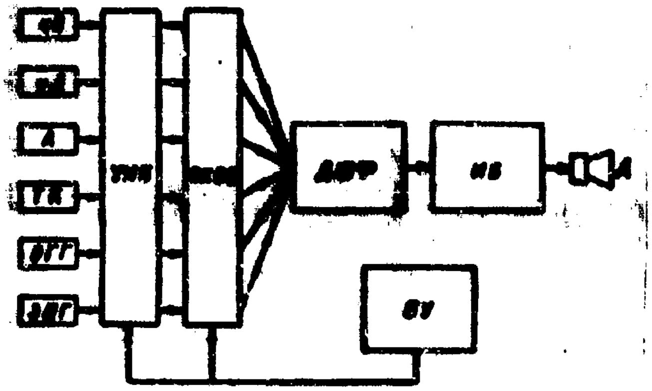

Fig. 44. Block diagram of automatic logical system (variation 2). ЧП — pulse-rate transducer; ЧД — respiratory-rate transducer; А — actogram transducer; ТК — skin-temperature transducer; ОГТ — oxyhemogram transducer; ЭПГ — electroplethysmogram transducer (for measuring blood supply to the brain); УИВ — amplifying-measuring units; СХОЗ — information selection and storage circuits; ДШФ — two-stage encoder; ИБ — indicator unit; БУ — control unit; Д — dynamic loudspeaker for supplying audio signal.

fix the specified values of parameters; d) a control system; e) encoders for determining specified symptom complexes in a combination of deviations (symptoms); f) signal indicator.

Six physiological indices were selected, of which three can be measured by the number of pulses per unit time [pulse rate (ЧП), respiration rate (ЧД), actogram (А)], and three can be measured as voltage levels [skin temperature (ТК), oxyhemogram (ОГТ), and cranial electroplethysmogram (ЭПГ)].

The measuring system for pulse counting is a binary flip-flop counter. The selection circuit is a logical "And" circuit with the necessary number of inputs. At the circuit output there is a storage cell flip-flop. The norm range is set up by connecting the inputs of the selection circuit to the necessary counter collectors. The circuit for the selection of te in the form of voltage levels works on the principle of a stabilitron pulse height discriminator and also has a storage-cell flip-flop. The control system automatically connects the storage cells and sets the counters at the initial state at the end of every measurement cycle (from 10 to 60 sec). For simplification of the circuit, only two states are selected: "Н" and "+". State "-" is determined in the first stage of the encoder by the absence of signals "+" and "Н". In the second stage of the encoder the logical operation of comparing the state of the six indices is performed and the output signal is shaped. The algorithm is given in matrix form (Table 12). The encoders are diode-matrix circuits.

Table 12. Algorithm for Logical System Operation

Parameter	Norm	Syncope	Collapse	Acute cardiac insufficiency	Parameter	Norm	Syncope	Collapse	Acute cardiac insufficiency
ЧП	Н	—	+	+	ТК	Н	—	—	Н
ЧД	Н	—	+	+	ОГТ	Н	—	—	—
Д	Н	—	—	—	ЭПГ	Н	—	—	—

High-Speed Digital Systems for Processing Physiological Information

Digital technology opens up absolutely new possibilities in the area of medical monitoring by providing the complete simulation of the physician's logic in those cases when it can be expressed by a specific algorithm. A digital system can work on a "flexible" program and pertains to the class of "diagnostic machines."

The application of a digital computer for diagnostic purposes is an absolutely new and little investigated field. On-board diagnostic machines are distinguished by the obligatory introduction of information directly from the astronaut. A. M. Zhdanov, V. V. Bogdanov, and L. A. Kazar'yan participated in the development of the first mockup of an automatic medical monitoring system on a specialized digital computer base [33, 36, 288].

The first experiment used an algorithm which was given in matrix form. This, however, was only a check of the possibilities of using a specialized digital computer (СЦВМ) [SDC] for processing medical information.

The SDC for automatic medical monitoring consisted of the following functional modules: an input unit [U_{in}] ($У_{ВВ}$), an arithmetic unit [AU] (АУ), a control unit [CU] (УУ), a magnetic operational storage [MOS] (МОЗУ), a permanent storage [PS] (ДЗУ), and an output unit [U_{out}] ($У_{ВЫВ}$). A block diagram of the SDC is shown in Fig. 45.

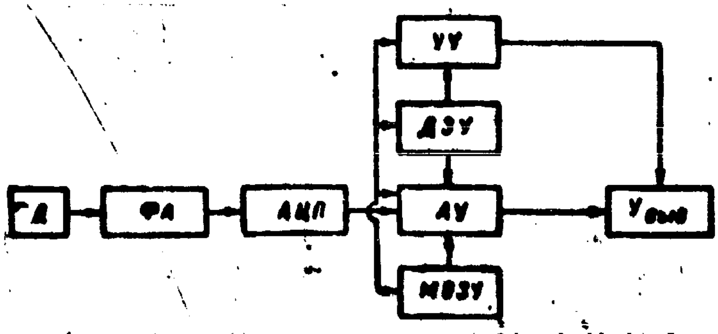

Fig. 45. Block diagram of a specialized digital computer used in an automatic medical monitoring system. Д – transducers; ФА – physiologic equipment; АЦП – analog-to-digital converter; АУ – arithmetic unit; УУ – control unit; МОЗУ – magnetic operational storage; ДЗУ – permanent storage; $У_{ВЫВ}$ – output unit.

The input unit consists of a number of analog-to-digital converters, the characteristics of which are given in Table 13.

The magnetic operational storage has the capacity necessary for storing current information proceeding from the converters during the measuring cycle.

Table 13. Characteristics Input Converters of Automatic Medical Monitoring System

Parameter	Type of converter	Accuracy of conversion	Speed of quantization
Pulse rate	Period-to-digit	±0.05 sec	–
Respiratory rate	The same	±0.2 sec	–
Skin temperature	Volts-to-digit	±2%	1 per minute
Motor activity	Frequency-to-digit	±1 cps	–
Galvanic skin response	Volts-to-digit	±2%	5 per second
Mechanical work of heart	The same	±1%	100 per second
Conditioned-motor response	Period-to-digit	±0.01 sec	–
Air pressure	Volts-to-digit	±2%	1 per minute
Atmospheric humidity	The same	±2%	The same
Air temperature	The same	±2%	The same
Carbon dioxide content	The same	±2%	The same
Oxygen content	The same	±2%	The same

With the development of an appropriate algorithm the MOS capacity can be brought up to 32 characters. Thus, for example, during the analysis of ballistocardiograms (seismocardiograms) it is not necessary to store all curve points; it is sufficient to determine only its characteristic points so that in subsequent measurements it is essary only to compare the recorded values with the new ones and correct them during the entire measuring cycle. The PS holds the machine-operation program and constant numbers (norm limits of every parameter). The PS capacity is equal to 1024 13-bit binary numbers. The AU is high-speed with several thousand operations per second and performs its computations with a fixed point. The output unit records data with the aid of a digital teletype (for operation under laboratory conditions), and also can send information to the telemetry system to an indicator to inform the crew.

An operational program of a digital computer for evaluating the state of an astronaut and life-support systems was constructed similar to the matrix table type analogous to Tables 10 and 11.

Figure 46 illustrates a sample of a recording obtained during laboratory tests of a SDC mockup. Simultaneously with the input to the SDC, direct recording of a number of parameters was performed on an ink recorder followed by "manual" data

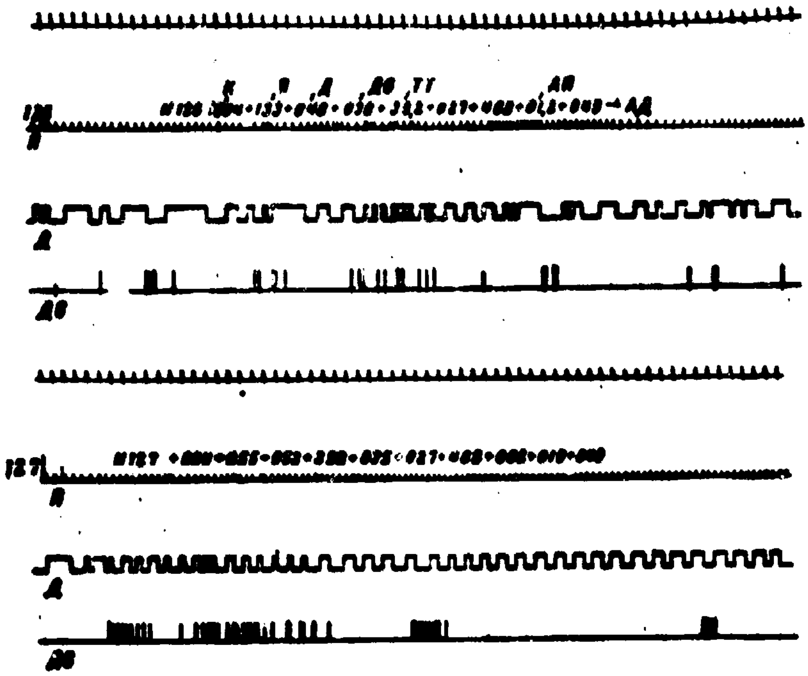

Fig. 46. Sample of recording obtained during laboratory tests of a SDC mockup with a medical monitoring program. П — pulse; Д — respiration; Дв — motion; АП — pulse arrhythmia; АД — respiration arrhythmia; TT — body temperature; К — code.

analysis. A comparative evaluation of "machine" and "manual" data processing indicated that only in 5% of cases were there observed any machine processing "errors." The causes of these errors consisted in the fact that interferences (short duration failures) were considered by the machine as useful information, while they were rejected in manual processing. Various algorithms can be suggested for machine detection of interferences [345].

The following stage of research was devoted to automating the medical research program. This was done in cooperation with V. A. Sharov and K. K. Chern'shev. First of all, the input of analog information from on-board physiological equipment to the memory unit of a digital computer was worked out. The quantization frequency of each parameter was selected in accordance with the requirements in Table 3. Input of an electrocardiogram, seismogram, pneumogram, sphygmogram, and other indicators was conducted.

Then by means of constructing curves for the discrete values of the parameters contained in the memory unit, the quality of operation of the converter was checked. A sample of a recording obtained by means of artificial "readout" of data from the machine memory is shown in Fig. 47.

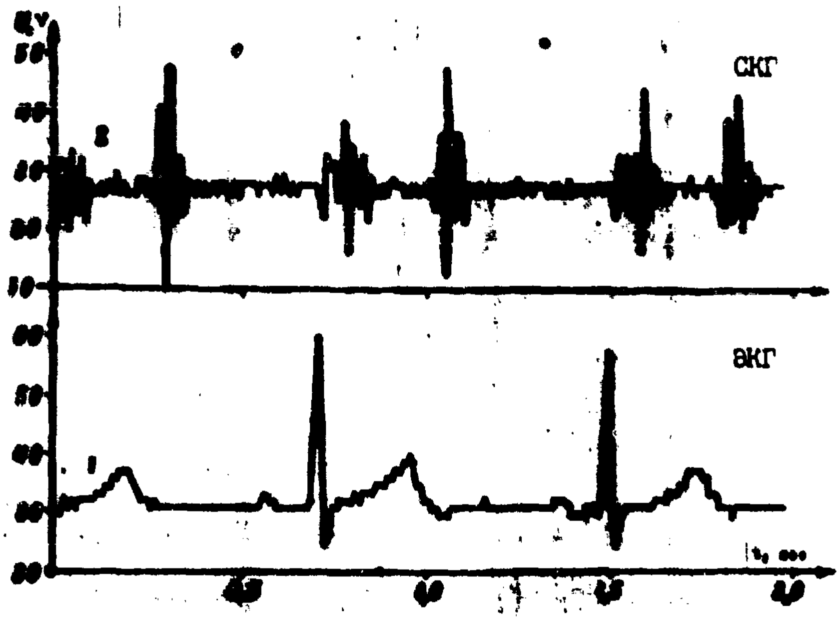

Fig. 47. Readout of discrete voltage levels depicting electrocardiogram (1) and seismocardiogram (2) signals from SDC memory.

The discrete values of the parameters were subjected to analysis in accordance with the developed algorithms. Figures were obtained at the machine output which characterized the various oscillogram indices. Thus, automatic interpretation of an electrocardiogram, seismocardiogram, sphygmogram, and electropneumogram was conducted with the aid of an SDC. The number of indices that were automatically computed amounted to 40. The most important things here, however, is a fundamental solution to the problem of data analysis directly in the research process. On the given stage of automation of medical research it was decided to be limited to the automatic computation of separate indices. The logical evaluation of indices and the making of a diagnosis are special independent problems, the solution of which requires extensive research.

CHAPTER 6

SOME PROBLEMS OF PHYSIOLOGICAL MEASUREMENT IN INTERPLANETARY FLIGHTS

The gigantic rate of development of astronautics is making flights to the Moon and planets of the solar system a reality. A large number of investigations today are being directed towards the solution of problems related to medical security in long-term and long-range interplanetary flights.

These investigations include the work on the creation of partially and completely closed ecologic systems [86, 237], work on the psychology of group activity and prolonged isolation [50, 92, 93], work on hypodynamia [125], on the selection of an optimum microclimate for spacecraft cabins [296, 703], and on establishing programs of work and rest in a long-term flight [74, 78]. Orbital variations for flight to the Moon, Mars, and Venus were subjected to detailed analysis [278]. However, the problems of medical security in interplanetary flights with respect to physiological measurements and diagnostics are not sufficiently discussed in literature.

Lovelace and Schwichtenberg point out that the further away man is from Earth, the more difficult it is to ensure the safety of his existence and return [608]. Of importance, therefore, is reliable medical monitoring and the collection of physiological data on the influence of interplanetary factors on man [451, 533, 610, 778].

It is assumed that man's conquest of space will consist of the fulfillment of a series of successively more complicated programs. Thus, the United States, after fulfillment of the "Mercury" program (twenty-four hour orbital flight), plans to first carry out the "Gemini" ("Twins") program — a two-man flight around the Earth for 14 days — and then Project "Apollo" — a flight to the Moon with a return to Earth [451, 528, 683]. In addition, the Americans intend to develop plans for the creation of piloted artificial earth satellites on the basis of the X-15 aircraft (Project

"Dyna-Soar") and are conducting research on the development of long-term space (orbital and interplanetary) stations [450, 451]. The construction of support and monitoring systems on a spacecraft essentially depends on the duration and range of flight and its character. Johnston proposes three types of monitoring systems: 1) the "Mercury" type; 2) the "Apollo" type; 3) systems for space stations [541].

A series of flight experiments with animals has been set up for investigating the influence of prolonged weightlessness, cosmic radiation, and other factors [552]. Projects have been planned which are involved with the search for extraterrestrial life [123, 355, 347, 595, 739, 592, 791], and in the more distant future, the realization of flights to Mars and Venus and the creation of an inhabited station on Mars and inhabited satellites of Venus and Jupiter has been proposed [568].

Thus, at present the most fantastic projects have become the subject of scientific investigation and even technical designing and modeling. Numerous trainers and simulators are being used to study the conditions of flight to the Moon and Mars and to clear up a number of questions related to prolonged hypodynamia, isolation, and so forth [601, 514, 498].

The prophetic words of the father of astronautics, K. E. Tsiolkovsky, are being fulfilled: "Earth is the cradle of humanity, but it is impossible to live forever in a c. dle." Humanity is now earnestly preparing to leave its cradle, the Earth.

Let us consider in greater detail certain questions of physiological measurement in a long-term (interplanetary) space flight.

Flight to the Moon and Entry into Space

It is natural that the nearest neighbor of Earth and its eternal satellite, the Moon, should be the first goal of astronautics. The U. S. Government has officially declared that reaching the Moon is one of its important national concerns. In view of this, besides the serious research being done, the United States is clearly attempting to carry out adventurous projects for a "one-way flight to the Moon" [590]. This project proposed to send a man to the Moon immediately, as soon as a reliable lunar-landing system is worked out, even before ensuring the possibility of his return. The astronaut will return in 2 or 3 years, when space technology has reached the appropriate level. It proposed to use a rocket as the astronaut's living quarters and to supply him with the aid of cargo rockets. It has been calculated that approximately 13 rockets a year will have to be sent to the Moon in order to support one man.

Similar anti-humane projects are alien to Soviet scientists. As long as the

conditions for a safe flight to the Moon and return are not ensured, we will not plan such a flight.

The large amount of work being conducted in the USSR on the creation of a reliable technical base for the realization of flights to the Moon and other planets is confirmed, for instance, by the statement made by the chief spacecraft designer in "Pravda" 1 January 1964.

One of the first tasks of space technology and space medicine consists of increasing the length of man's stay in outer space. American scientists have planned to carry out a 14-day two-man orbital flight in the next few years (Project "Gemini"). This project is a logical development of the "Mercury" program and its prime mission is to prepare for a lunar flight, including the testing of new space systems, rockets, and equipment, and also experimenting with the entry of one man into space [381]. It has been proposed that the first manned flight in a "Gemini" capsule will be carried out in 1964 and it will be orbital [363]. The "Gemini" is a two-man spacecraft with a volume 50% larger than that of "Mercury" and twice as heavy. Its shape is the same as the "Mercury" capsule. The craft has two ejection seats. One of the pilots sits at the control panel, and the second watches the instruments which indicate the operation of the on-board systems. They have spacesuits with a 15-minute oxygen supply. It is possibly to leave the craft in a spacesuit while in orbit with a 30-minute oxygen supply [488]. Regarding the physiological measurements, they essentially will not differ from the measurements conducted under the "Mercury" program [381].

Certain changes in the physiological monitoring program are planned in reference to the "Apollo" craft. First of all, they propose to use "minor" telemetry since the duration of flight and the necessity of active participation in control of the craft make wire communications between the astronaut and the on-board equipment very inconvenient.

Several new research methods plan to employ phonocardiography. Total equipment weight is approximately 2.5 kilograms and power consumption is 25 watts, including 23 watts for relay and motor operation. Output voltage is 1.5 volts [387, 811].

An "Apollo" capsule should be used in the fulfillment of the LEM (Lunar Excursion Module) program. This program anticipates the creation of a three-module spacecraft: a 5-ton control module, a 21-ton engine module, and a 12.5-ton lunar module. The control module will contain three astronauts (the "Apollo" craft proper). Two astronauts will transfer to the lunar module in lunar orbit and descend to the lunar

surface. Landing and takeoff from the Moon is accomplished with the same engine. After entering lunar orbit and docking with the main craft, the astronauts will again transfer from the lunar module to the "Apollo" craft [682, 809]. This, in broad terms, is the American lunar flight project.

Problems of the realization of a flight to the Moon have been agitating the representatives of various sciences for a long time: astronomy, rocket technology, biology. The Soviet Union has an undisputable priority in the development of these problems as well as in the first practical results. On the night of 13 to 14 September 1959, the second Soviet spacecraft reached the surface of the Moon and placed a banner bearing the seal of the USSR in the region of the western part of the sea of Rains. In October 1959, a Soviet automatic interplanetary station photographed the far side of the Moon and transmitted the photographs to Earth.

These outstanding results of Soviet science are involved with astronomical, mathematical, and scientific-technical research, which originated with the works of K. Tsiolkovsky. The problems of flight to the Moon are considered in detail in the monographs by V. I. Levantovskiy [157] and A. A. Shternfel'd [278].

The preparation for a flight to the Moon requires a thorough study of the conditions which man will encounter on this planet. It is known that the Moon is a dead and uninviting world. The absence of an atmosphere, the sharp fluctuations in temperature, cosmic radiation, and meteoritic danger — this by far is not a complete list of the factors which must be taken into account when organizing a lunar expedition [157, 357, 609]. The first investigations of the Moon will be carried out with the aid of automatic instruments [157, 627]; however, manned flight will involve a great number of unstudied factors.

Lowrey and Ray, in considering the "human factors of a flight to the Moon," along with others, note the following psychological factors: isolation, disorientation, mental fatigue, motivational disturbances, insomnia, a sensation of the "unknown," and others [609].

It is clear that medical monitoring and detailed medical research are a necessary element of any lunar program. For the purpose of preparing and training astronauts, special trainers and simulators have been developed both for investigating their reactions during in-flight spacecraft control in flight [603, 808] and during landing [383], and also while they are on the Moon [783].

A flight to the Moon will require the continuous monitoring of basic functions with information storage and transmission during alternate communications periods

with Earth. There should also be the possibility of sending warning signals to the crew from an automatic on-board device which processes both physiological and technical information [288]. After landing, one of the most critical operations will be the astronauts' descent to the surface of the Moon, which will demand medical monitoring with indications of astronaut condition on board the craft.

A man on the Moon will accomplish active and purposeful tasks. The construction of a lunar base, the obtainment of air, water, and food from lunar materials, the use of solar radiation as a source of energy – these are the tasks connected with supporting astronaut life. Since the day-time temperature of the lunar surface reaches 100°, and at night drops to -121°, immediately after the astronauts arrive on the Moon, they must dig into its surface layer or make a shelter for protection from extreme temperatures and radiation which is not weakened by the atmosphere as on Earth [783]. Inasmuch as the life of people on the Moon (for the first time) will depend on their ability to perform various forms of activity, medical monitoring and medical research should occupy an important place in the lunar-conquest program.

A significant place in medical support of human activity on the Moon apparently will be occupied by biotelemetry systems of the "spacesuit-to-spacecraft" type, which will be employed to transmit biological and technical information and to conduct two-way radio communications [40].

Medical monitoring during entry into space and on the surface of the Moon involves the use of various sensors and electrodes, amplifiers and radio links. Now there already are concrete proposals on the problems of constructing a physiological measurement system to be used for these purposes. In cooperation with K. P. Zazykin, N. P. Sasonov, and V. R. Freydel', we proposed to use the elements of intracabin telemetry systems for medical monitoring during entry into space and on the surface of planets [40]. This proposal was dictated both by limitations in volume, weight, and power consumption of the equipment which can be taken on the flight, and also by the single concept of medical monitoring, i.e., the comparability of data obtained on the Earth, in space, and on the Moon. The sensors and electrodes for medical monitoring, and the amplifiers and transmitter of intracabin telemetry can be considered as the source of information for the "spacesuit-to-spacecraft" radio link. After adding a power amplifier to the transmitter of the intracabin biotelemetry system, it is possible to considerably increase the communications range. It is possible that the number of physiological parameters to be monitored during entry and on the surface of the Moon should be increased as compared to intracabin monitoring. It is

expedient to introduce a number of research measurements. Of importance in such systems, apparently, will be the measurement of the hygienic parameters of the spacesuit and two-way radio communications. Solar batteries may be used to supply power to the radio equipment of the spacesuit.

Experimental instruments which derive their power from photocells have already been described in literature: e.g., a pulsometer in the form of a carbon microphone with an amplifier having a consumption of 2 ma operates from storage batteries with recharging from selenium photocells [588].

The "spacesuit-to-spacecraft" radio link is a version of "long-range" dynamic biotelemetry and differs in its parameters from the dynamic telemetry systems that are applied inside a cabin in sports medicine (Table 14).

Table 14. Characteristics of Dynamic Telemetry Systems

Index of system	Space medicine		sports medicine
	inside cabin	entry into space and on surface of Moon	
Range of operation	up to 10 m	1-10 km	50-2000 m
Service life	1-30 days	3-12 hours	up to 3 hours

In connection with the given characteristics, we can propose a classification biotelemetry systems in astronautics on the basis of range criteria (Fig. 48). We propose to distinguish five types of radio links: ultra-short-range, short-range, medium-range, long-range, and ultra-long-range.

Ultra-short-range radio links are designed for research and monitoring at distances up to 1 m. Their areas of application are a "Vostok" or "Mercury" cabins, and also investigations of animals under conditions of free movement inside small locations (cages). Systems of this type may employ inductive methods for supplying power to the telemetry equipment and may use implanted systems with a biological power supply.

Short-range radio links are basically intracabin "minor" telemetry systems with a range of operation up to 10 m. In reference to terrestrial conditions, short-range radio links can be hospital biotelemetry lines, certain forms of sports biotelemetry (inside a gymnasium), and others. The maximum range of action of short-range radio links can be 50 or 100 m.

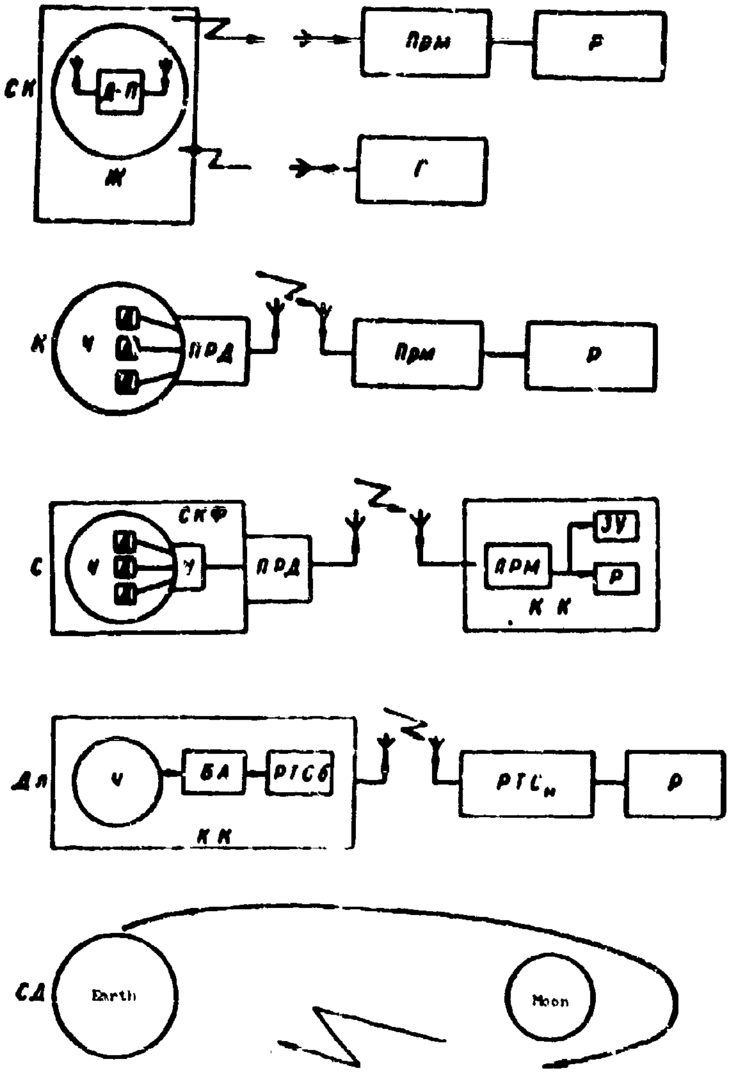

Fig. 48. Classification of space biotelemetry systems. СК — ultra-short-range; К — short-range; С — medium range; Дл — long range; СД — ultra-long-range; Ж — animal; Ч — human; Д — sensor; Д-П — sensor-transmitter; Прм — receiver; Г — generator; Р — recorder; ПРД — transmitter; У — amplifier; СКФ — spacesuit; КК — spacecraft; ЗУ — memory unit; БА — on-board equipment; РТСб — on-board telemetry system; $РТС_н$ — ground telemetry system.

Medium-range radio links include the "spacesuit-to-spacecraft" systems which will be used during entry and on the surface of the Moon and planets. Its indicated range of up to 10 km is tenative inasmuch as the limits of direct visibility on the Moon, due to its large curvature of surface, are restricted to a total of 1 km. Communication will be extremely difficult on the Moon since the absence of an ionosphere makes it impossible to employ radio links without direct visibility between the

receiving and transmitting antennas. In connection with this there are proposals concerning the realization of communications with the aid of seismic waves from microexplosions that can be produced in strictly specified time and spread through the hard crust of the Moon [819]. During entry it may possibly be required to transmit physiological data from an astronaut at a distance of up to 10 km.

From the general-medicine point of view, medium-range radio links pertain to the fields of sports medicine and the physiology of work.

Long-range radio links are used to transmit data from a spacecraft or airplane to Earth and also to transmit biological information from one point to another on the surface of the Earth. The maximum distances in this case can reach 20 thousand km. Experiments on the transmission of physiological data by radio have already been conducted. Thus, in 1959 an electrocardiogram was transmitted from the aircraft carrier "Franklin Roosevelt," which was near the shores of Greece, to Washington [722]. Recently, an electrocardiogram was transmitted through the American artificial earth satellite "Telestar".

Ultra-long-range radio links provide for the transmission of information at distances of over 20 thousand km. Radio links of this type will be applied for communications with a spacecraft on a circumlunar trajectory and during landing on the Moon, and with space stations at a large distance from the Earth and with a lunar base. An essential role is played here by coordination of the volume of information with the carrying capacity of the channels.

It is necessary to employ methods of optimum encoding. Long-range radio links, in the fullest sense, amount to "space telemetry."

The organization of a flight to the Moon as one of the important aspects requires a study of the problem of the transmission of biological and physiological information from the Moon to the Earth. Certain sides of this problem were considered in Chapter 2.

Flight to Mars and Other Planets of the Solar System

The next space goal after the Moon will be Mars [798]. This assumption ensues from a large number of astronomical, biological, and technical considerations [157, 150, 234, 821]. There are many different projects for a flight to Mars. One of these projects anticipates the creation of a spacecraft that consists of two capsules (one reserve in case of damage to the craft). Each capsule consists of three modules: 1 — for life support during an extended flight; 2 — for orbiting Mars, landing and

takeoff; 3 – for control in stages: launch, correction of orbit, and return. The crew is made up of 3-8 men [798].

The Douglas Company, under contract to NASA, developed detailed specifications for all systems to provide for a 3 to 10 man expedition to Mars. The duration of the expedition is to be from 1 to 3 years. The length of stay on Mars will be 10-50 days [807].

A project for an interplanetary spacecraft with a nuclear engine for a four-man 15-month flight to Mars was recently published [815]. The craft should be assembled in a satellite orbit. A special two-man module is being developed for landing on Mars.

One of the chief characteristics of the physiological measurement and information system of interplanetary spacecraft is the participation of a physician (crew member) in its operation. The necessity of the participation of a physician in an interplanetary expedition is mentioned in many works [798, 635, 336]. The United States has even named its first physician-astronaut candidate, a famous specialist in the field of space physiology, Doctor Roman [792].

However, as we know, the first physician in space was a Soviet citizen, Boris Borisovich Yegorov, a member of the "Voskhod" crew. Of definite importance in the sense of gaining experience in medical support of extended space flights will be the orbital space stations whose launching will precede the interplanetary flights [365, 521, 547, 681, 796].

The long duration of an interplanetary flight and the presence of a physician in the crew, and also the use of on-board automatic data processing and storage systems requires the development of new principles of construction of physiological measurement and information systems. First of all it is necessary to determine the main tasks which must be performed with the aid of physiological measurements on an interplanetary spacecraft. It is possible to cite at least four such problems:

1. Operational medical monitoring carried out by the spacecraft physician periodically in separate periods of flight.

2. Planned, dispensary, general-medicine investigations of crew members for the purpose of evaluating the state of their health and collecting scientific information on the influence of the factors of an extended interplanetary flight on the physiological functions of man.

3. Special medical investigations conducted for the purpose of more thorough monitoring of separate systems and organs and for diagnosing diseases which may

appear during flight.

4. Transmission of the basic results of all physiological measurements to Earth.

Considering that the physiological measuring system has a means of collecting, converting, transmitting, and recording data, we will try to illustrate the possible structure of such a system which would correspond to the problem on hand. First we shall consider the ways of solving separate problems.

Medical monitoring on an interplanetary spacecraft should be carried out periodically according to a definite program, and also beyond the program, when there is a possibility of the appearance of dangerous deviations in the state of health of the crew members. All similar situations cannot be foreseen beforehand. Some of them can be cited now: the performance of repair operations in space, a considerable increase in radioactivity, disturbances in air-conditioning and heat-control systems, braking of the spacecraft when executing a maneuver and during landing, and so forth. In these cases the necessary sensors and electrodes are attached by the physician (or by the astronaut himself) and the appropriate on-board equipment is turned on (the intracabin telemetry system is used in this instance). Data must be fed in generalized form (and, at the desire of the physician, in primary form) to a specially equipped medical panel. These data must be fixed simultaneously in a memory unit and then transmitted to Earth in reduced ("compressed") form during alternate communications periods.

Planned, dispensary, medical investigations of the crew must be sufficiently detailed in order to ensure the timely detection of even slight deviation in the state of health and the obtainment of sufficiently complete scientific information. It is natural that these investigations will be conducted by a physician (by a specially trained individual), whose duties will include not only monitoring the quality and authenticity of the data obtained, but also interpretation of the data. A predetermined, standardized, and tested set of procedures with a sufficiently wide range and a specific program will make it possible to use reliable algorithms for primary on-board automatic data processing. Special reference aids will also be required for evaluating the results of investigations. If we assume that these investigations can be conducted once a month, the storage of the recordings accumulated during an entire flight becomes a complicated problem. Therefore it is necessary to preliminarily work out these problems with physicians and engineers in order to determine the degree of preliminary data processing for on-board storage as well as for transmission to Earth.

Special medical investigations may include: investigations foreseen beforehand in case of the appearance of definite shifts of individual organs and systems or planned physiological measurements of research value; investigations necessary for a more precise determination of the state of the crew members who have developed a symptom complex that is still unknown on Earth.

In the first case, if a set of sufficiently large and diverse procedures involved with definite programs can be used for simultaneous machine processing of results, the matter is considerably more complicated in the second case. Here the possibilities of employing research methods which are not in the planned programs must be ensured. To do this, the physician and the crew members with appropriate engineering training must be oriented in the diagnostic aspects of contemporary physiology and must have various sensors and instruments for organizing such investigations which will be necessary in the developing situation. As an example, it is sufficient to indicate the possible necessity of measuring spinal fluid pressure, determining pH and temperature in the stomach, and studying the albumin fractions in the blood.

Diagnostic problems under the conditions of an interplanetary flight are closely related to problems of physiological measurement. But besides physiological measurements, one should correctly collect the necessary information, inspect and examine the patient, logically interpret all these data, and make a correct diagnosis. It is known that when making a diagnosis (and consequently, when selecting the treatment) the physician's experience is of tremendous importance. It is doubtful that it would be possible that the physician of an interplanetary spacecraft will be able to gain the necessary experience in all fields of medicine. The requirements of universality that are imposed on him exclude the possibility of gaining a large amount of medical experience in sufficiently diverse areas: e.g., in dermatology and neuropathology. This means that the diagnostic abilities of the physician must be reinforced by the contemporary facilities of computer technology and mathematics, and also by the appropriate reference aids. Thus, the physiological measurement and information system of the spacecraft may be said to be a "diagnostic" one. A block diagram of a diagnostic system is shown in Fig. 49. The construction of diagnostic systems on a spacecraft has a specific character which is related to the following factors:

a) the volume of the memory and the high-speed operation of the on-board computer are limited; b) the most diverse data in the most diverse form will be fed

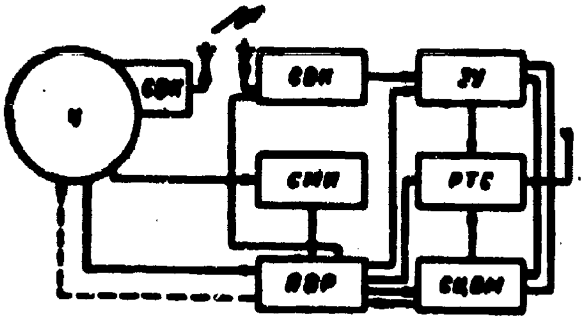

Fig. 49. Block diagram of the "diagnostic" system of an interplanetary spacecraft. Ч – individual; СБК – medical monitoring system; СМИ – medical research system; ПВР – physician's panel; СЦВМ – on-board specialized digital computer; РТС – telemetry system; ЗУ – memory unit (dotted line indicates "feedback" between physician and patient).

into the diagnostic system (oscillograms directly from an individual, numerical data, complaints and information in the form of codes, and so forth); c) the number of probable diagnoses is very great; d) the possible appearance of symptom complexes which are still unknown and cannot be foreseen beforehand.

The difficulties of creating a universal diagnostic system on an interplanetary spacecraft to a certain extent may be decreased by means of developing special microfilm references, and also by making it possible to solve particular diagnostic problems with the on-board computer, using programs which can be developed, if necessary, by mathematicians on the spacecraft with the participation of a physician. One also should not forget the possible advisory help from Earth; but this is already related to the next task, i.e., the transmission of information to Earth.

It is a well-known fact that the limited power supplies and longer "astronomical" distances in interplanetary flights do not permit broad-band and continued radio communications. It is assumed that the capacity of telemetry channels and the duration of transmission will decrease hundreds of times and the exchange of information between the spacecraft crew and Earth will be very limited.

It is now difficult to perform the appropriate calculations; however, it is absolutely clear that the transmission of not only oscillograms, but also numerical data will be impossible. Coded, generalized information apparently will be the basic means of exchanging data with the Earth. Therefore, we should now begin work on the creation of "new code language" for expressing all the necessary data and concepts of medicine and biology which may be demanded in an interplanetary flight.

Just as there exists an international radio code, where a combination of three letters expresses whole concepts (SOS – request for help; QRA – question concerning location), space medicine also should possess a corresponding means of exchanging information. We should also bear in mind the possibility and necessity of automatic code sending by an on-board computer for transmission to Earth after every routine

or special physiological investigation.

Thus, the diagnostic measurement system of an interplanetary spacecraft will essentially differ from the systems known at the present. The comparative characteristics of three types of physiological measuring systems (for short-term space flights, for extended space flights, and for interplanetary spacecraft) are given in Table 15.

Table 15. Characteristics of Various Types of Physiological Measurement and Information Systems

Short-term (up to 5 days) flights	Extended (up to one month) flights	Interplanetary flights
All sensors and electrodes are on astronaut during flight	Astronaut has only a minimum number of sensors and electrodes for medical monitoring, most of them attached by the astronaut himself for a brief examination period	Sensors and electrodes of medical monitoring system and all remaining sensors are attached by spacecraft physician
Astronaut is wired to on-board equipment	Intracabin radio link used for medical monitoring	Intracabin radio link used for medical monitoring
On-board medical equipment is controlled automatically from Earth or from on-board timer.	In addition to automatic and program control, there is manual control	Equipment is controlled manually
Physiological data are recorded only in the period of direct communications between spacecraft and ground points	Most physiological data are recorded by memory units in the period of no communications with Earth, followed by automatic transmission of all information to Earth	Data recorded with the aid of on-board equipment with storage in processed form. Only a small portion of generalized data is transmitted to Earth
Transmission of physiological information in the form of oscillograms	Transmission of physiological information only partially in the form of oscillograms	Physiological information transmitted to Earth only in generalized form
	Majority of data transmitted in digital form and in generalized code form	

Biological Indications of Interplanetary Space

The first "astronauts" were animals. Before a man is sent into space, the route of his future flight is extensively investigated with the aid of various biological specimens. The orbit in which the "Vostoks" accomplished their triumphal flights was repeatedly probed by satellite vehicles with animals on board. Similar methodology for flight experiments in space has been adopted by both the USSR and the United States. It is now possible to definitely say that a special trend has appeared in astronautics, i.e., biological indications of interplanetary space; its

mission includes:

1 — a study of the biological action of the factors of space and interplanetary flight; 2 — a biological evaluation of life-support systems of spacecraft intended for manned flight; 3 — the creation of biological warning indicators.

These three trends can be reduced to the following: biological intelligence, biological monitoring, and biological warning.

The physiological measurement and information system of a spacecraft and an interplanetary vehicle is one means of biological intelligence and biological monitoring. The application of the same physiological methods and the same equipment for investigating animals and humans is expedient both economically and methodologically. This ensures the comparability of the data obtained in the first flights of animals with the data from medical monitoring and medical research in manned flights. Therefore, the development of physiological measurement and information systems should anticipate th possibility of their application for investigations with animals. Thus, the physiological measurement system of the "Vostok" spacecraft was first tested with the dogs Chernushka and Zvezdochka.

Brief investigations with animals can be conducted with the aid of implanted sensors and electrodes which are wired to the on-board equipment. However, a flight experiment lasting up to a month and more requires contactless methods of collecting formation. Implanted transmitter-sensors or integral systems and other methods of ntactless physiological research have been developed for this purpose.

Miniature instruments have been devised for installation on animals [473]: e.g., a 20-gram transmitter with i-meter range of operation for installation on the back of a rat [795]. It was possible to measure the body temperature of a dolphin swimming in a basin [807]. Miniature transmitters were built into eggs which were placed under penguins. This made it possible to study incubation temperature [416].

Contactless methods include methods of investigating the motor activity of mice by means of recording the oscillations of a cage mounted on springs with automatic counting of the number of pulses produced by a piezoelectric sensor [786]. An electromagnetic method is prepared for recording the respiration of mice. In this method, a 4 × 4 × 20 mm magnet is placed under the animals' skin and inductance coils in which there has appeared an emf proportional to respiratory and motor activity are placed in a chamber [415]. A barometric method is used for contactless recording of respiration, i.e., recording insignificant pressure drops in a hermetic chamber

caused by respiration [319]. Methods for contactless recording of electromyograms have been developed [317].

The most promising are the sensors and systems which are implanted in the animal's body and transmit information through undamaged skin under conditions of free behavior. Diverse variations of subcutaneous transmitters are described in many works [318, 419, 349, 467, 728]. The most serious achievements were made by Ettlesson's group [352, 420, 421, 422]. A three-channel FM-FM system was developed. The parameters were selected in such a way as to check the feasibility of obtaining oscillograms from within an organism in different frequency ranges: low-frequency — respiration, medium-frequency — electrocardiogram, and high-frequency — phonocardiogram. One nickel-cadmium cell was used for the power supply. It was recharged by an electromagnetic field. The time of continuous operation without recharging was 12 hours. The frequency of the transmitter was 45 Mc and the output power was 2 milliwatts. At present this group of authors is developing systems for implantation with the application of elements of molecular electronics. They propose to record cardiac output, oxygen saturation of the blood, and so forth. There are reports concerning attempts to launch monkeys with three-channel systems implanted in the kidney region on "Atlas" rockets. There are indications that, in spite of the unsuccessful launchings, satisfactory telemetry curves were obtained [393].

A serious problem is that of supplying power to implanted devices. Inductive power supplies are economically unprofitable and complicate the on-board equipment. Experiments on the use of the galvanic (polarization) potential difference that appears between two electrodes made from different metals and placed at different points of the body are promising. The best results were obtained with the aid of stainless steel and platinum placed subcutaneously and in the abdominal cavity, respectively. On a load of 500 ohms it was possible to obtain a power of 115 microwatts with a voltage of 0.23 volts. This turned out to be sufficient for supplying power to a 500-kc generator [672, 673].

Thus, in the methodological respect, the use of animals as biological indicators in an extended space flight is fully substantiated both theoretically and practically.

There are two stages of biological intelligence. First of all, the problem of survival is solved during the study of a new space route. This is the first stage of biological intelligence in outer space. In connection with the "Vostok" flights, this stage was the flight experiment with Laika, whereas the flights of the dogs

Belka, Strelka, and others were the second stage of biological intelligence, the mission of which consisted in detailed investigations of the biological action of the factors of space flight on a living organism. The second and third Soviet orbital spacecraft were veritable "flying" scientific laboratories. However, even in flights where chiefly problems of survival are studied, a large amount of scientific material of a research nature is collected. We have already determined a tentative list of subjects for biological intelligence in outer space. Dogs are the first on the list. They are the classical subjects of Russian and Soviet physiology. Their circulatory and respiratory systems are very similar to analogous human systems. Mice are suitable subjects in the methodological respect for studying metabolism [331, 644]. Soviet space research has gained much experience in studies of mice and special containers for the extended flight of mice on a spacecraft have been developed [42]. Investigations of the biological action of cosmic rays are being conducted on plants, microbes, flies, and rodents. American researchers have used primates for the purpose of biological intelligence. France has conducted a flight experiment with a cat.

Prime attention in biological intelligence is given to obtaining a sufficient volume of information necessary for establishing the degree of biological action of a particular factor or a group of factors. Biological monitoring is conducted to check out life-support and recovery systems. An example of biological monitoring was the flight of the dogs Chernushka and Zvezdochka.

Biological signalling refers to measurements with the obligatory application of automatic data processing systems. The signal which a measurement system generates can indicate the normal or pathological state of a biological specimen in connection with the action of some extreme factor. One of the first signal indicators was the biocell, i.e., an instrument for automatically recording the vital activity of microbes which was tested during the flights of the second and third Soviet orbital spacecraft [18, 299]. The biocell was designed to transmit information on the amount of pressure in an airtight capsule containing microbes of butyric acid fermentation and a nutritive solution. Normal gas formation in the process of the vital activity of the microbes ensured a corresponding growth of pressure in the capsules. A comparison of the amount of pressure measured in flight with the standard value makes it possible to detect changes in the vital activity of microorganisms.

Biological signalling on manned interplanetary craft will be of particular

importance. Miners, when going underground, take along a canary, which is very sensitive to an increase in the concentration of mine gas and intensive motor activity warns of danger. An astronaut in flight also should have similar biological signal indicators which would warn him of various dangers. The variety of extreme factors of interplanetary space dictates the necessity of using various living organisms, some of which would warn of some dangers and others would warn of other dangers. At present, methods have been developed for telemetric transmission of information from the most diverse biological specimens: dogs [349], mice [795], monkeys [352], and birds [689]. There are experimental data on the fact that the pulse rate of mice is directly proportional to the magnitude of G-loading, and consequently, can indicate limiting reactions to acceleration [707]. With the aid of tensiometer pickups implanted in the heart, it is possible to detect changes in the contracting ability of the myocardium as a result of the action of G-loads, weightlessness, and other factors [316, 598]. A signal indicator of high pressure inside the stomach of animals has been described, which can be used for indicating certain influences involved with the appearance of meteorism [656]. Finally, we may mention the high sensitivity of certain microbes to ionizing radiation, which also is of interest for biological indication in space [269]. Thus, the development of methods for various biological (including physiological) measurements on animals, microbes, plants, and insects plays an important role in the solution of problems of the biological indication of space routes. However, the effective application of various bioindicators is possible only on the basis of a clear idea of the spectrum and limits of the effects which must be detected.

A biosignalling system on board an interplanetary craft has an independent value, but is connected with a single diagnostic system. It uses the on-board computer and has outputs on the physician's panel. It is important to note the circumstance that the introduction of biosignal indicators will free the astronaut from a number of additional investigations, inasmuch as the biological specimens on the craft will reliably warn of possible dangerous effects.

The problems of biological indication play an important role in planning the further steps for the conquest of space. The principle of preliminary investigation of various routes and space systems with the aid of animals and other biosubjects remains as a firm law of astronautics [18, 38, 74, 85, 238]. Animal flights also will precede manned flights in the future. The United States is planning 49

biological experiments in space in the near future, including several 30-day flights. Investigations will be conducted with monkeys and other animals, and also with plants [797]. They propose to set up a number of specialized experiments to clear up the genesis of certain physiologic phenomena in weightlessness. For instance, a special capsule for investigating blood circulation has been developed [394]. Special experiments are proposed for studying the influence of radiation on the brain [816] and behavioral responses [395].

Biological Control

The astronaut is not only one of the objects of a physiological measurement and information system, but is also included in the complicated system of spacecraft control. The complication of space flight programs will demand more active participation from the astronaut in the control process. At large distances from Earth, under conditions where there can appear unforeseen circumstances, man should be able to make decisions and carry them out. Therefore, the requirements imposed on man as the operator of the control system must be coordinated with the characteristics of this system, and conversely, the control system should be designed in such a way as to ensure the possibility of control by the man. The problem of "man-machine" has lately been given greater attention on the part of space biology specialists [107, 138].

One of the functions of a physiological measurement and information system consists in monitoring astronaut efficiency, i.e., determining his ability to carry out the control process. Depending upon the data obtained during alternate communications periods from Earth, a "go" or "no go" can be given to switch from automatic to manual control. Blocking of "manual" control, depending upon the state of the astronaut, can be performed automatically after processing the physiological information with the on-board computer. This is the simplest variation of the use of physiological information for control (biological control).

Biologcial control is a new captivating field, a branch of cybernetics. In biological control systems, information taken from a living organism controls the operation of technical systems: e.g., an automatic syringe can be actuated [183]. The United States has published data on a bioelectric control system that functions under the action of G-loads, i.e., under conditions when an astronaut cannot physically control the spacecraft [633, 745, 770]. There are proposals concerning the use of biological information for purposes of automatic regulation in a closed

ecologic system [88, 121, 271] and for controlling emergency-rescue or life-support systems [12, 753]. Actually, the issuing of recommendations to the crew which is carried out by an automatic on-board computer is also an example of biocontrol. Here the recommendations obtained on the basis of processing physiological information control the actions of the crew [753].

One of the first biological control systems is the "artificial hand" (control of muscle biopotentials) which was created by V. S. Gurfinkel', A. Ye. Kobrinskiy, and their associates [99, 142] and was successfully demonstrated at the Brussels World Fair in 1958. Biological control can be carried out with the use of the most diverse information. Thus, we know of projects where artificial respiration control was carried out by biopotentials of the phrenic nerve or respiratory muscles [210, 638] and X-ray machine control with the aid of cardiac biopotentials [100, 172]. Attempts have been made to manufacture anesthesia devices controlled by brain biopotentials [330, 338]. Brain biopotentials have been used to actuate a relay [408]. Not only bioelectric processes are used for biocontrol, but also other biological phenomena. Thus, for instance, a signal on the given pressure level is used for automatically regulating the height of arterial pressure. When the pressure drops below the given level, a specific dose of noradrenaline is automatically introduced into a vein [822]. The mechanical properties of muscle have also been used for biocontrol [61.]. All this makes the idea of using the principles of biological control very tempting when designing automatic spacecraft systems. Indeed, only an automatic space system that considers the state of living organisms on board a spacecraft can ensure the most optimum regime of flight and maximum crew safety. We can isolate at least three groups of problems which can be solved by means of automatic systems with the introduction of biological information: a) voluntary control, with the aid of muscle biopotentials, of spacecraft systems which must be turned on, turned off, or continuously regulated in the period of action of extreme factors which make manual control physically impossible; b) involuntary control, with the aid of various biological indices, of automatic spacecraft systems by ensuring optimum living and working conditions for the crew: e.g., an air conditioning system; c) voluntary and involuntary control of emergency-rescue systems during the action of vitally dangerous factors.

A biological control system, or the biological part of a complex system of automatic control, can be illustrated in the form of a number of series-connected

blocks: a) a block for the collection and amplification of primary biological information; b) a block for processing primary information and shaping signals which are utilized for carrying out the control algorithm; c) a computational block which generates commands on the basis of a specific algorithm; d) an electric drive which transmits control commands to servomechanisms: relays, electric motors, and so forth.

The use of biological information for controlling technical systems should not decrease, and converoely, increase the operational reliability of these systems. Therefore, all biological control blocks, and especially the block for collection and amplification of primary information, must be given very stringent requirements. Only information whose obtainment under conditions of space flight can be firmly guaranteed should be used for control. For screening out interferences or signals of no value in the control process, the information obtained from a living organism will be subjected to thorough automatic analysis according to special algorithms which monitor the authenticity of the data introduced. Separate indices which occupy a definite place in the control algorithm must be isolated from the flow of information in order to shape control signals. Thus, for instance, various indices of independent value in various algorithms can be isolated from an electrocardiogram, such as the length of the RR interval and the index of pulse arrhythmia (ΔRR max); the integral index of delta-rhythm and so forth can be isolated from an electroencephalogram. As an example, Fig. 50 illustrates the block diagram of a biocontrol system for emergency rescue on the basis of the use of voluntary (electromyogram) and involuntary (pneumogram) commands. The same figure schematically depicts the control algorithms.

Today we can already come up with a certain idea of the list of biological indices which could be used in biological control systems at the present level of development of medical electronics. These include biocurrents of the muscles, brain, and heart, indices of the mechanical work of the heart, external respiration, heat control, the functional state of the central nervous system, and, in particular, the vestibular apparatus. It is also clear that the methods of introducing biological information into a control system must be diverse, depending upon the conditions of flight and the possibilities of the procedures and techniques. It is possible to imagine three versions of information input; a) input from a limited number of sensors and electrodes on the body of an astronaut for medical monitoring; b) input from sensors and electrodes that are specially attached only for the time of

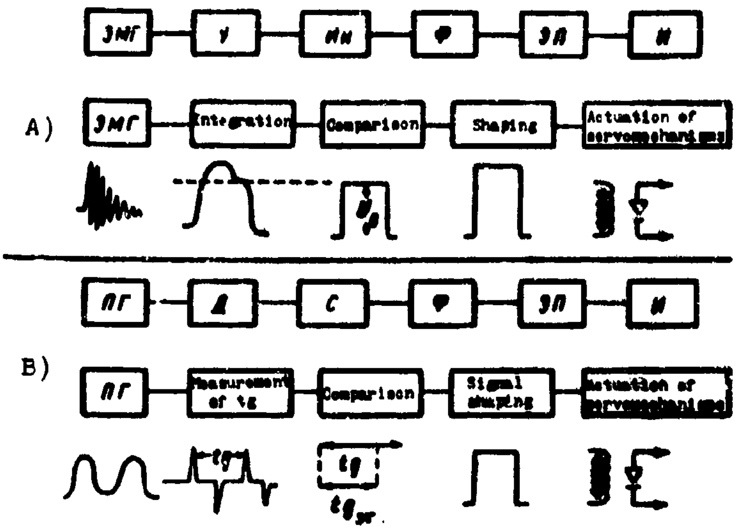

Fig. 50. Block diagram and operational algorithms of voluntary (A) and involuntary (B) biocontrol systems. ЭМГ – electrodes for electromyogram recording; У – amplifier; ИН – integrator; Ф – shaper; ЭП – electric drive; И – servomechanism; ПГ – sensor for pneumogram recording; Д – circuit for measuring the length (tg) of the respiratory cycle; U_B – reference voltage; С – comparison circuit; $tg_{ЭМ}$ – given length of respiratory cycle.

realization of the control process; c) input from sensors and electrodes that are attached for a short time for detailed examination of an astronaut. It is then necessary to memorize certain indices which characterize the state of the crew for the time prior to the next examination period.

Such an examination can be planned or a special one conducted by a command from an automatic system which requires additional information for selecting the most optimum program of its work;

d) input from sensors and electrodes on animals, which perform the role of bioindicators (signal indicators).

The most complicated question in problems of the application of the principles of biological control to automatic space systems are the operational algorithms for the computational block that generates commands for technical devices. The algorithms must consider specific combinations of technical, physical, and biological indices and possess the necessary reliability in the sense of unity of final decisions in the event of the appearance of unexpected situations. The principles of duplicating the input signals and multiple monitoring should be used. Various combinations of biological and physical factors must be studied and their interrelationships must be expressed in mathematical form. There is still a lot of scientific research to be done on algorithms of biological control under conditions of space flight. Now it is even difficult to imagine the general trends of such work. However, the expediency and necessity of introducing the principles of biological control in astronautics is indubitable. Therefore, all the facts obtained by space medicine and biology must be analyzed from the point of view of the possibilities of algorithmization of the control process in space flight on the basis of a thorough calculation of the

biological and technical factors.

Biological control in astronautics is not a fantasy, but a necessity. The increase of the duration and range of space flights and the beginning of the age of conquest of other celestial bodies will require the maximum use of human and technical capabilities in all stages of flight. The use of biological information for optimization of automatic space systems opens up new possibilities towards the conquest of space. Thus, for instance, of importance to ultra-long-range flights is the problem of artificial hibernation [247, 385, 524]. The solution of this problem involves research in the field of biocontrol. The possibility is not excluded that certain sections of automatic systems will use various types of animals that are best adapted for the perception of certain effects and can best provide the information necessary for control. Effects can be perceived by animals both directly and also in the form of electrical stimuli. Telestimulation of animals with the aid of electrodes implanted in the brain is presently the subject of serious investigations [340, 399, 659, 760]; the possibility of controlling the work of the muscles, heart, urinary bladder, and other systems is being studied [335]. However, man undoubtedly has the leading role in spacecraft control, and the information on the state of the crew should be the main criterion which determine the program and regime of flight. Research in the field of application of the principles of biological control in astronautics will make it possible to ensure maximum spacecraft reliability and maximum space flight safety.

P A R T II

METHODS PHYSIOLOGICAL RESEARCH

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CHAPTER 7

CARDIOVASCULAR RESEARCH METHODS

The cardiovascular system supplies organs and tissues with oxygen and nutrients and removes metabolic products from them. Because of the perfect regulation of all functional components of this system, a wide range of adaptive responses to the varying conditions of the medium is accomplished. Space flight imposes high requirements on the circulatory apparatus. The isolated and complex action of G-loads, weightlessness, emotional tension, and other factors causes various compensator shifts on the part of the cardiovascular system and the organism on the whole. The necessity of research on the effect of the factors of space flight on the heart and vessels stipulated the application of methods for pulse and electrocardiogram recording in all flight experiments with no exceptions both with rockets and also with artificial earth satellites and spacecraft. A large program of cardiological research was carried out during the flights of the second and third Soviet orbital spacecraft. At present, the number of investigations being conducted on the circulatory system under conditions of space flight considerably exceeds the number of investigations on the other systems of the organism. Correspondingly, the procedures and methods in this area have been developed considerably to a fuller extent. As a result of the accumulation of experimental and theoretical data, it is possible with rightfully speak of the formation of a specific branch of space physiology, i.e., space cardiology.

The basic tasks of space cardiology consist in developing research methods, studying the mechanisms of the compensative-adaptive responses of the circulatory system, investigations of cardiovascular disorders that are possible in flight, and the means for their treatment. The methods of space cardiology, just as those

of space physiology on the whole, are basically well-known clinical and laboratory procedures which have been modified for the conditions of space flight, and only in certain cases have new methods and procedures been specially developed. Therefore, general information on the essence of the methods, the history of their development, and their functional capabilities is very brief. At the same time, the appropriate fields has reported on certain results of the application of the described methods and procedures in space flights.

Finally, in conclusion, a review of some new methods is given in reference to cardiological research in space.

The selection of cardiological methods for research in space flight was dictated by considerations that are well-known in clinical medicine and physiology. Inasmuch as the compensative-adaptive responses of the cardiovascular system are accomplished in two ways (by changing the minute volume and changing the redistribution of the blood), methods which characterize the function of the myocardium as well as peripheral circulation must be used.

In addition, also of great importance is the study of the neural and the neuro-endocrine mechanisms for regulating blood circulation; however, this question is considered in detail in subsequent chapters.

From the methods of investigating the functional state of the myocardium, to the most developed is considered to be electrocardiography. However, in virtue of the specific character of space flight, practically all questions of electrocardiographic procedure had to be reconsidered, including the selection of leads, the fixation of electrodes, bands of recorded frequencies, and methods of analysis. Even more difficult was the application of such methods as ballistocardiography, kinetocardiography, and phonocardiography in space research.

Difficulties also arose in the development of methods for investigating peripheral blood circulation. The application of sphygmography, plethysmography, and arterial oscillography in space flight required radical modification of these methods and essentially the creation of new methods and procedures specially adapted for spacecraft conditions.

In examining the questions of the application of physiological research methods in space flight, one should consider the various aspects. First of all, physiological methods are necessary for the solution of medical monitoring problems. Monitoring the state of an astronaut's cardiovascular system includes a number of absolutely obligatory measures that are undertaken to ensure flight safety. The

pulse rate ("Signal" transmitter) was not randomly selected as the physiological parameter whose transmission on the "Vostoks" was conducted continuously during the entire time of flight. The basic requirements of a method from the point of view of the problems of medical monitoring are high reliability and diagnostic effectiveness. It is absolutely necessary to devise methods for operational evaluation of the parameters of medical monitoring when narrow-band channels are used for their transmission. Therefore, special consideration is given to methods for recording, transmitting, and analyzing pulse rate.

The solution of research and diagnostic problems requires the use of a wide range of methods and procedures which cover the various aspects of activity of a functional system.

Space cardiology already now possesses a sufficiently large set of methods and procedures which have been tested under space flight conditions. A significant number of new methods has been developed on the basis of evaluating the results of flight experiments for application in the future. Many cardiological methods that are applied in clinical medicine and experimental physiology have a potential value for astronautics [527]. Finally, it is important to note the clinical aspects of space cardiology: the diagnostic check of new methods in a clinic and the use of the data obtained for improving the interpretation of the results of flight experiments.

Electrocardiography

Electrocardiogram Recording in Humans

Electrocardiography is one of the most wide-spread methods for studying the heart. An electrocardiogram makes it possible to directly evaluate three functions of the cardiac muscle: automatism, excitability, and conduction [260]. As it is known, electrocardiograms are recorded in humans by using electrodes that are attached at various points on the surface of the body. Questions of the selection of leads, the attachment of electrodes, and ensuring a minimum transition resistance on the electrode-skin section are among those basic methodological problems on the solution of which depends both the quality of the recordings obtained as well as their information content. Electrocardiogram recording under the conditions of space flight required the development of an essentially new method. It was necessary to obtain recordings of the same quality as in the laboratory, whereupon the prolonged attachment of electrodes to an astronaut's body should not cause discomfort, interfere with his activity, irritate his skin, cause sores, or result

in any pain.

The problems of recording electrocardiograms in space flight to a certain extent are similar to analogous problems in sports medicine and the physiology of work. Therefore, the first investigations were devoted to the study of appropriate electrocardiographic leads and methods for attaching electrodes. Leads recommended by L. A. Butchenko were tested [56], including [NEBU] (НЭБ) leads, [N1] (H1) and [N2] (H2) leads, leads proposed by the Sverdlovsk Biotelemtry Group [75], and leads described by American authors [437, 447, 480, 613]. It is natural that the selection of points for attaching the electrodes was limited to the chest, where the level of muscular interferences and the degree of electrode displacement during movement is considerably lower than on the extremities.

In addition, the recordings obtained from the chest possess a high diagnostic effectiveness. Thus, for instance, Jacono and Luisada propose to simplify electrocardiography technique by introducing a total of 3 chest leads instead of the 12 standard ones (1, 2, 3 single-pole leads from the extremities and 6 chest leads) [542].

As a result of experimental investigations, two bi-polar chest leads which were called MX and DS (2). The advantages of these leads consist in the following: high noise-resistance (minimum level of muscle biopotentials); convenience of attaching electrodes; high diagnostic effectiveness.

The electrodes in the MX lead are arranged on the center of the sternum on the level of the manubrium and the ensisternum; the electrodes in the DS lead are placed along the midaxillary line on the right and on the level of the fifth intercostal space on the left (Fig. 51). Thus, the MX lead belongs to the sternal group, and the DS lead belongs to the axillary group of leads described by Roman [679].

Special work has been conducted on finding methods for attaching electrodes. An adhesive system was tried first, using glue [BF-6] (БФ-6), cleol [mastisol], glue No. 88, and collodion. Electrodes were tested in the form of thin siliver plates, silver foil, spiral wire, and a mixture of silver powder and collodion (Trate et al.). The most suitable method was that of using glue No. 88 or BF-6. A similar method of attachment was used in Yu. A. Gagarin's flight. The electrodes were attached G. S. Titov's in flight by adhesion (in the MX lead) and with the aid of a harness (in the DS lead) [N. A. Agadzhanyan, I. G. Akulinichev, et al.]. A complete transition to the harness brace was subsequently made. This system

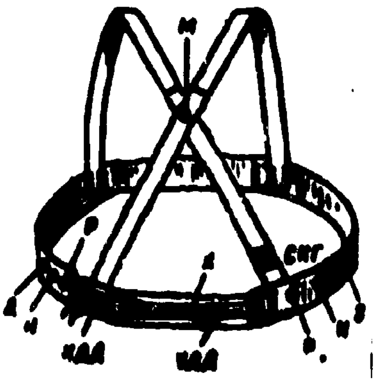

Fig. 51. Harness for attaching sensors and electrodes. УДД – carbon-type respiratory sensor; КДД – contact respiratory sensor; СКГ – seismocardiographic sensor; electrocardiographic electrodes; H – neutral electrodes; P – electrodes for rheography (electroplethysmography).

includes the above-described chest harness with built-in electrodes on orlon linings and two straps which cross on the astronaut's chest and are fastened on his back. Rubber pieces mounted in the harness create conditions for tight adhesion of the electrodes to the skin.

The interelectrode resistance is held constant by using contact paste. Best results are obtained with VNIIMIIO [All-Union Scientific Research Institute of Medical Instruments and Equipment] paste No. 2 [65].

The value of the interelectrode resistance in electrocardiographic investigations has been studied by many authors. L. A. Vodolazskiy considers that a high interelectrode resistance results in the appearance of frequency and amplitude distortions of the electrocardiogram, an increase in the S wave, and a decrease in the positive P, R, and T waves [69].

L. A. Vodolazkhkiy proposed complex method for treating the skin which lowers the resistance to 10-15 kΩ. The skin is treated with a paste made from soap cream containing finely ground pumice; then the skin is rubbed with ether, and only after that is the electrode paste applied. This method has been used very often in sports medicine various modifications [300]. A detailed study of interelectrode resistance with various methods of skin treatment, types of pastes, and electrode sizes was conducted by V. V. Rozenblat and A. T. Vorob'yev [218]. They showed that for brief recordings it is most expedient to use a liquid suction-cup electrode with skin treatment leather by Nikiforov's mixture (alcohol + ether 1:1).

Regarding electrode construction, from the various types – reticular [756], foil [746], laminar with wire brush [750], and disk [106, 437, 612, 679] – the last type was selected as the most convenient for attacnment. The construction of the electrode was selected so that it could be easily attached to a chest harness, would not press its sharp edges into the skin, have a recess for depositing paste, and be sufficiently light. The electrode diameter is 18-20 mm. The electrode is made from pure silver. It is interesting to note that the American researchers employed stainless steel electrodes in space flights steel [437, 788, 789, 790]. The value of the proper selection of material for electrodes is pointed out, for instance,

by an article published by Luschina and Phipps in 1963 [612]. The authors studied the interelectrode resistance for electrodes made from a mixture of Ag and AgCl in various proportion. The most effective electrodes, i.e., the ones which provide the least interelectrode resistance, turned out to be electrodes containing 3 parts Ag and 7 parts AgCl.

We should also note the proposal concerning dry wire electrodes made in the form of a screen which is pressed to the skin with a moistened sponge [497, 631].

Undoubtedly, research on the most suitable electrodes and points for their arrangement for electrocardiography under conditions of space flight must be continued. It is possible, for instance, to indicate the extremely promising model of an electrode which was proposed in the German Democratic Republic [776]. Three disks with a diameter of 20-30 mm are placed on insulated plate at a distance of 5-10 mm. The extreme disks are active and the central ones ("ground") weaken the pickups.

To improve the quality of electrocardiogram recording, certain authors propose the use of amplifiers with a limited frequency band. J. Roman [679] indicates that a limitation of the band from above to 100 cps does not affect the clinical information content of a recording, to 50 cps the electrocardiogram practically does not change, and to 25 cps it introduces certain distortions. Limitation of the band from below to 0.2 cps does not change the clinical information content. The influence of muscle interferences at various degrees of narrowing the band of an electrocardiographic amplifier was investigated in detail by A. Freiman and his associates [437]. Optimum solutions were obtained for a noisy channel, whereby a change of the frequency scale created a maximum signal-to-noise ratio.

As was shown above, the electrocardiographic amplifiers in the physiologic equipment on the Soviet "Vostok" spacecraft had a uniform frequency-response curve in the frequency band of 0.1-40 cps, which fully corresponds to the practical as well as the theoretical requirements, especially one considers the high signal power in a lead from the chest.

Norms of the magnitude of electrocardiogram waves and intervals in selected leads were studied by means of comparing them with standards. This was done by examining 20 young persons. Tables 16 and 17 give the comparative data.

As can be seen from the tables, the duration of the QRS and QT intervals in the MX lead is somewhat longer than in the II standard, and the duration of the PQ interval is somewhat shorter. However, the variance of values in the MX lead is less.

Table 16. Normal Variations in Duration of EKG Intervals in II and MX Leads

Statistical index	Intervals					
	PQ		QRS		QT	
	Leads					
	II	MX	II	MX	II	MX
M, sec	0.150	0.141	0.086	0.092	0.385	0.392
V, %	20.6	14.9	40.7	17.5	12.5	5.4

Table 17. Normal Variations in Amplitude of EKG Waves in MX, DS, and Standard Leads

Wave	Leads	Rests		Holding breath after inhalation		Holding breath after exhalation	
		M, mv	V, %	M, mv	V, %	M, mv	V, %
P	I	[illegible]	42,2	[illegible]	[illegible]	0,10	[illegible]
	II	0,110	40,0	[illegible]	42,5	0,12	115,0
	III	[illegible]	76,4	0,07	[illegible]	0,06	[illegible]
	MX	[illegible]	57,5	0,52	[illegible]	[illegible]	[illegible]
	DS	0,110	43,6	[illegible]	54,31	0,11	[illegible]
R	I	0,72	[illegible]	[illegible]	[illegible]	0,76	[illegible]
	II	[illegible]	22,4	[illegible]	17,5	[illegible]	22,5
	III	0,42	[illegible]	0,76	45,7	0,47	[illegible]
	MX	[illegible]	37,3	0,57	42,3	[illegible]	[illegible]
	DS	0,19	24,4	1,16	[illegible]	1,20	[illegible]
T	I	[illegible]	[illegible]	0,25	61,4	[illegible]	[illegible]
	II	[illegible]	[illegible]	0,21	64,0	[illegible]	37,0
	III	[illegible]	476,2	0,06	215,0	0,02	[illegible]
	MX	[illegible]	[illegible]	0,73	42,6	[illegible]	[illegible]
	DS	[illegible]	37,1	0,44	54,3	0,42	[illegible]

The P wave in the MX and DS leads is the same as in the I in II standard ones; at inhalation, it essentially increases in the MX lead and decreases in the DS lead. The same, but less expressed, changes are observed in the III and I standard leads, respectively.

A small R wave and a deep S wave is observed in the MX lead. The R wave is high in the DS lead (higher than in the standard leads). At inhalation, in distinction from the standard leads, the amplitude of the R wave in the DS and the MX hardly changes. The T wave in the MX and the DS is higher than in the standard leads (especially in the MX). The changes of the T wave at inhalation are analogous to the changes of the P wave.

The wave variance in the MX and DS leads; just as in the I and II standard leads, is 30-50%. The variance in the DS lead is less than in the MX.

To determine the direction of the electrical axis of the heart on electrocardiograms that were recorded in DS and MX leads on the basis of the analogy of

the MX and I, DS and III standard leads, A. D. Yegorov established the correlation equation

$$Y = [illegible] + [illegible]\,X,$$

where Y is the magnitude of angle α in the standard leads; X is the magnitude in the MX and DS leads, which are considered as the I and III standard leads, respectively.

To determine angle α for the MX and DS leads, we can use existing tables or axiometers, considering MX and DS, respectively, as the I and III standard leads. The obtained magnitude of angle α must be substituted in the given formula. It is necessary, however, to indicate that this formula is useful only for calculating angle α in healthy young persons and under conditions of rest. Clinical observation did not confirm the validity of this method for determining the electrical axis of the heart in MX and DS leads in persons with cardiac pathology (Yu. N. Volkov).

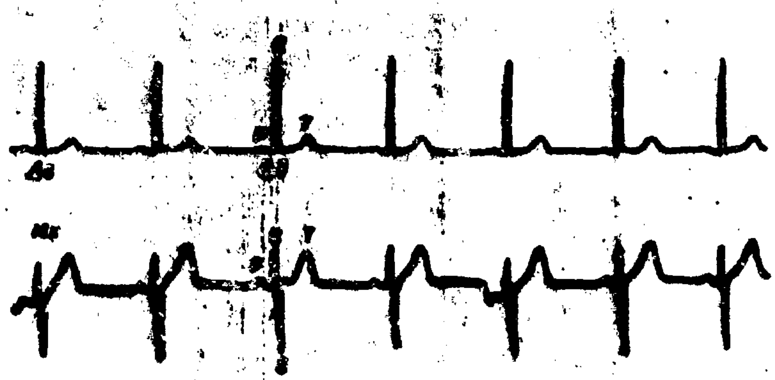

Fig. 52. Electrocardiogram in MX and DS leads.

Figures 52-53 show samples of electrocardiograms in MX and DS leads and synchronous recording of DS and I standard leads while the test subject was exercising. The noise immunity of the DS lead is very demonstrative.

MX and DS leads were used during the flights of the "Vostok" spacecraft. Astronauts Yu. A. Gagarin and G. S. Titov had their electrocardiograms recorded in both of these leads; the EKG's of the other astronauts were recorded only in the DS lead.

Figures 54-55 show samples of electrocardiograms that were recorded in Soviet astronauts during flight on the "Vostoks." As can be seen from the electrocardiograms of V. F. Bykovskiy, which were recorded on the first and last day of flight, the quality of the curves was sufficiently high for five days.

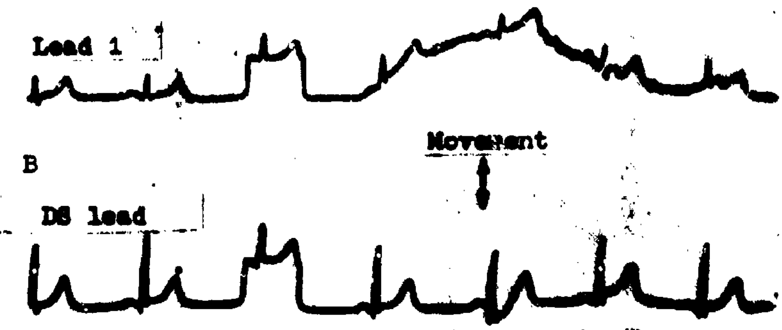

Fig. 53. Noise immunity of DS lead during movement (synchronous recording of first standard and DS leads).

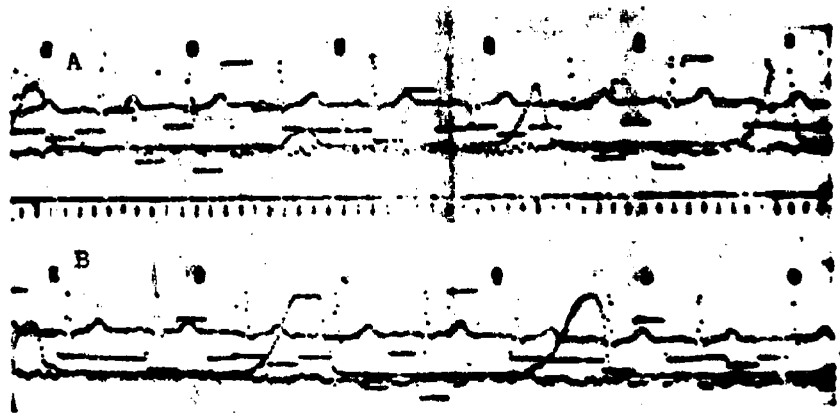

Fig. 54. Samples of electrocardiograms of Yu. A. Gagarin (A) and V. V. Nikolayeva-Tereshkova (B) that were recorded during space flight.

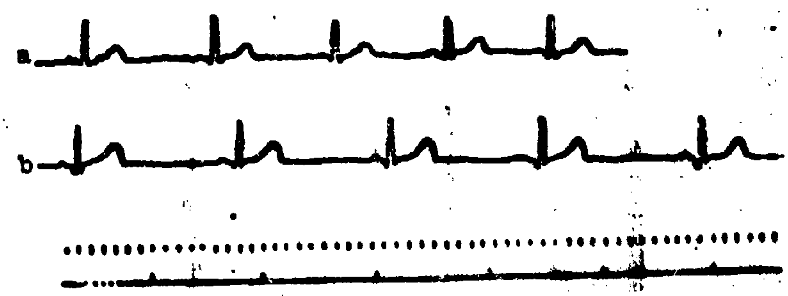

Fig. 55. Electrocardiograms of V. F. Bykovskiy which were recorded on the first (a) and fifth (b) day of flight.

For the purpose of studying the diagnostic feasibilities of MX and DS leads, Yu. N. Volkov examined 56 patients with various diseases of the cardiovascular system; this was done at our suggestion as the S. M. Kirov Military Medical "Order of Lenin" Academy [VMOLA]. It was established that MX and DS leads quite clearly reflect the pathological processes that occur in the cardiac muscle. It was

detected that in a number of cases these leads make it possible to reveal pathological changes, even in those cases when they are not noticed during an investigation with the application of the usual leads.

Electrocardiogram Recording in Animals

Electrocardiographic research on animals under conditions of space flight is methodologically simpler than on humans. The heart biopotentials of animals are recorded by means of implanted electrodes.

During the flights of the second-fifth Soviet orbital spacecraft with animals, electrodes were employed in the form of a 10 x 10 mm reticule made from multiple tantalum wire [MKhM-40] (МХМ-40). The lead part of the electrode was a continuation of its reticular part and was coated (in a number of cases) with polyethylene. The surgical technique and procedures were developed by A. R. Kotovskiy. The methods for picking up the biopotentials were specially investigated on 20 dogs with the cooperation of M. N. Osipova [31]. Recording was conducted with the aid of seven needle electrodes which were placed on three extremities and in four pectoral positions [G1, G3, G5, G9] (Г1, Г3, Г5, Г9). Eighteen leads were recorded in each dog. All animals were examined while lying on their stomach. The investigations were conducted at the same time of day.

As it is known, the electrocardiograms of dogs are distinguished by expressed respiratory arrhythmia and considerable variance in wave shape and amplitude, which is not connected with any influences on the animal [266, 743, 618]. The calculation of these peculiarities was facilitated by introducing an arrhythmia index (Δ R R) and structural complex formulas. The arrhythmia index is determined by subtracting the minimum duration of the cardiac cycle from its maximum duration (Δ R P = R $R_{\text{макс}}$-R $R_{\text{мин}}$). The structure of the EKG complex was designated by letters in accordance with the number of expressed waves. Lower-case letters expressed a decrease in the waves, upper-case letters indicated their normal magnitude, and upper-case letters in parentheses denoted an increase in the waves. To indicate splitting, pointing, and two-phase character of the waves, the following arbitrary symbols were placed above the appropriate letters: (V), (/\), (+ -). Displacement of intervals PQ or ST was designated by a horizontal line above or below the letters. Figure 56 illustrates samples of recordings that were obtained from the dog Shutka. The structural formulas are shown under the complexes. The whole variety of complexes can be reduced to five typical structures: PQRST, PQRT, PRT, PST, and PRST.

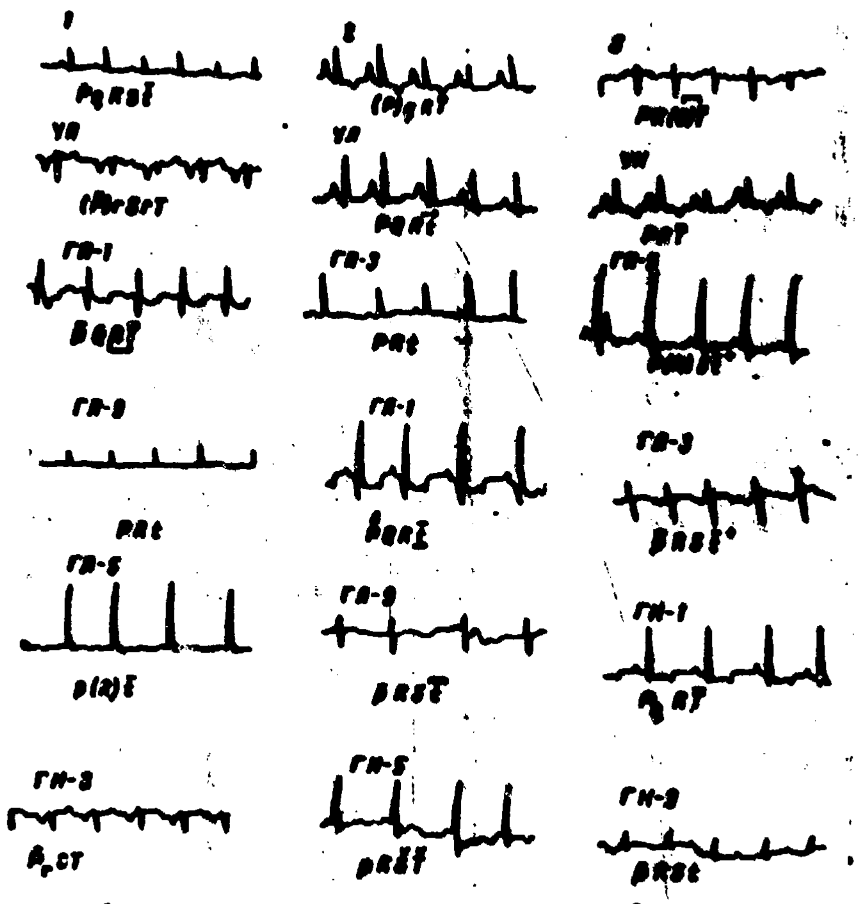

Fig. 56. Electrocardiogram of a dog in 18 leads (letters designate structure of complexes).

In our opinion, only changes of the structural type of a complex as a result of some influence can serve as a criterion of electrocardiographic pathology in animals. Therefore, when selecting EKG leads, it is most expedient to have leads with different types of complexes. Table 18 shows the distribution of structural types for leads (on the basis of our research data).

As can be seen from the table, P R T is more frequently encountered in leads 2, 3, [UN] (УН) and [UL] (УЛ); type PRST is more common in leads [GP-3] (ГП-3), [GP-5] (ГП-5) and [GL-3] (ГЛ-3) type PQ RT is found most often in leads [GP-1] (ГР-1) and [GL-1] (ГЛ-1). These three types of structures are the most wide-spread. The stablest structure is possessed by leads 2, 3, UN, UL, GP-3, GL-1, and GL-3.

Table 19 gives the data on certain EKG indices in dogs according to the results of processing the recordings in the second standard lead.

Table 18. Distribution of Structural Types of Electrocardiograms with Respect to Leads

Lead	Structural types of electrocardiograms				
	[illegible]	PQ ST	[illegible]	[illegible]	[illegible]
1	1	8	[illegible]	—	—
2	4	—	[illegible]	—	1
3	—	—	[illegible]	—	4
VR	1	—	17	—	2
VL	1	8	[illegible]	—	—
VF	1	3	[illegible]	—	—
FR	—	11	2	—	7
FR-3	—	1	3	—	10
[illegible]	—	—	6	—	12
[illegible]	—	15	—	1	1
[illegible]	—	—	[illegible]	2	8
[illegible]	—	2	[illegible]	—	13
[illegible]	7	4	[illegible]	—	—
[illegible]	[illegible]	4	[illegible]	—	8
[illegible]	—	2	6	—	10

Table 19. Value of Certain Electrocardiographic Indices in Days

EKG-index	Mean values	Limits of normal variations	EKG-index	Mean values	Limits of normal variations
RR, sec	0.7	0.4-1.2	P, mv	0.35	0.2-0.5
QT, sec	0.28	0.15-0.7	R, mv	1.1	0.7-1.5
PQ, sec	0.11	0.09-0.13	T, mv	0.3	0.1-0.6
QRS, sec	0.05	0.03-0.08			
СП, %	32	26-48	Electrical axis (degrees)	72	50-85

These data fully correspond to the materials of other authors. Thus, M. G. Shevchuk and M. M. Bereshnitskiy [274] indicate values of PQ and QRS within the limits of 0.08-0.13 sec and 0.04-0.08 sec, respectively. R. Jain [541] gives the following mean figures: PR = 0.13 sec, QRS = 0.048 sec, P wave = 0.26 mv, and R wave = 1.41 mv.

When selecting EKG leads for dogs one should consider the possibility of obtaining maximum information with a minimum number of leads. With the use of one lead, one should recognize leads 2, UN, and GP-3 as the best; for two leads, 2 and GP-1, UL and GP-3, UN and GL-1, 3 and GL-3 can be recommended.

Changes in wave amplitude most frequently depend on the change of the heart position in the chest [266, 618]. Thus, according to our data, the biggest respiratory variations in amplitude are found in leads GL-5, GL-9 and GN-9. To

determine the electrical position of the heart, it is convenient to use UL-UN leads. The amplitude variations of the R wave in the UL lead usually are connected with a change of the electrical axis in different phases of the respiratory cycle.

In accordance with the experimental data obtained, electrodes were implanted in "astronaut dogs" in the region of the extremities, and in the 1st and 5th intercostal spaces. To prevent the animals from damaging the electrodes, the electrodes on the extremities were transfered to the region of the back, near the shoulder and hip joints. Control recordings showed that the character of the curve did not change essentially.

Table 20 gives data on EKG leads in animals that made flights on the second and fifth Soviet orbital spacecraft.

Table 20. Electrocardiographic Leads in Dogs Which Made Flights on the Second and Fifth Soviet Orbital Spacecraft

Dog	EKG lead		Dog	EKG lead	
	1 (conditional)	2 (conditional)		1 (conditional)	2 (conditional)
Belka	1	2	Mushka	2	—
Strelka	2	GP-3	Chernushka	1	2
Pchelka	GP-3	—	Zvezdochka	1	2

When recording the electrocardiograms in the animals, it was necessary to take into account various kinds of interferences Animal movements can cause high-amplitude muscle biopotentials which distort the electrocardiogram. During movements there also occur intertranspositions (muscles, skin, subcutaneous cellular tissue), which causes displacement of electrodes and the appearance of interferences in the form of "driving" of the isoelectric "drivings" also can be observed in time with respiration. For the surgical technique and implantation procedure have an important value in eliminating these interferences. Electrodes must not be placed in the thickness or on the surface of large muscles. They must be sutured to tendons or fasciae in regions which are far from the points of attachment of the muscles. It is expedient to place the electrodes as close as possible to the periosteum; then their displacements during animal movement will be minimum. It is also necessary that the lead wire does not pass near any strong muscles.

Serious inconeniences in experimental work are related to interferences from the a.c. network (50 cps). However, inasmuch as animal research was basically conducted in a metallic capsule, which was a sort of shield, no special

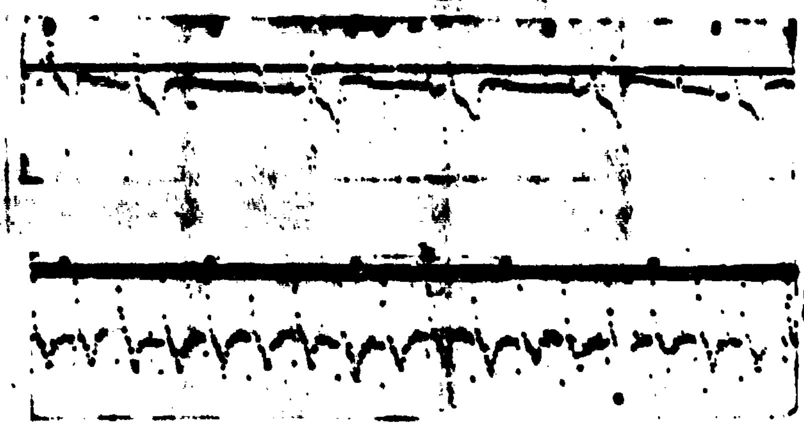

Fig. 57. Electrocardiogram of the dog Zvezdochka during propelled flight (b) and in weightlessness (a).

measures for protection from network interferences were required. It was important only to ensure good grounding of the chamber and the equipment.

Electrocardiogram recording in animals during flight was carried out on several channels. The quality of telemetry recording was good. Only during propelled flight, under the influence of vibrations and G-loads, and also due to muscular tension of the animals, was recording sometimes of low quality. Figure 57 illustrates samples of electrocardiograms of dogs which were obtained in different phases of flight. The interpretation of telemetric electrocardiogram recording is not especially difficult. All the necessary indices can be determined by it.

Pulsometry

Changes in the rhythm of cardiac contractions are one of the important compensative-adaptive responses of the circulatory system. An increase in pulse rate to known limits leads to an increase in the minute volume and to an acceleration of blood circulation. The blood supply to the cardiac muscle during a high pulse rate is improved by dilating the coronary vessels with a parallel increase in the oxygen consumption of the myocardium [309].

Pulse rate is one of the most important indices of the functional state of the cardiovascular system [303, 116, 418]. It is known that the ancient physicians distinguished hundreds of pulse varieties and even made diagnoses on the basis of the pulse. In our time, the evaluation of shifts in pulse rate during functional tests has become a permanent thing when performing a medical examination [106, 162, 300]. A space flight may also be considered as a unique cardiovascular test.

The quantitative characteristics of reactions are determined by comparing the pulse rate in various stages of flight with the initial pulse rate at rest and during the simulation stresses which are accompanied by the action of the factors of space flight (centrifuge, prolonged hypodynamia, etc.).

To monitor pulse rate during prolonged periods, and also when there is no direct telemetry contact with the spacecraft, a special instrument was developed, i.e., the electrocardiophone (see above). This instrument converted heart biopotentials which corresponded to the Q R S complex of an electrocardiogram into square pulses 0.15 sec in duration. To send AF-modulated transmission in the rhythm of heart contractions, a shortwave "Signal" transmitter was used, which operated continuously during the entire orbital flight. A sample of an electrocardiophonogram recording is shown in Fig. 58. The electrocardiogram is used for more exact calculations of pulse rate.

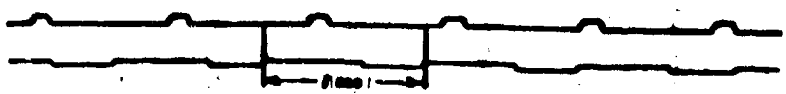

Fig. 58. Sample of an electrocardiophonogram recording made in flight "Signal" system.

The measurement of pulse rate – pulsometry – has an important practical value in space medicine in providing for medical monitoring of an astronaut inasmuch as during considerable periods of time the electrocardiophone is the only source of physiological information.

Pulsometry methods have recently started to be intensely developed. Thus, instruments for visual and audio pulse monitoring have been employed in operations [392, 397]. Instruments have been devised which make it possible to record or observe a continuous curve of the change in pulse rate, i.e., a pulse tachogram [680, 715]. The USSR is mass-producing the [PT-2] (ПТ-2) pulse tachometer. Descriptions have been published concerning instruments designed to count the total number of pulse beats in an extended period of time: e.g., in days [358, 693]. Of importance is an analysis of the time intervals between adjacent pulse beats, i.e., cardiointervalography [397, 220, 311]. Other methods may also be used for pulse analysis [4, 384, 485, 594, 640].

The pulsometry method is extremely convenient from the point of view of information transmission and instrumentation. Pulsometry requires neither broad-band

channels nor high-quality amplifiers. Determination of pulse signals is possible even in electrocardiograms with considerable distortions. All this makes it very expedient to completely use the diagnostic information contained in a sequence of signals which characterize the rhythm of heart contractions.

The simplest method of pulse analysis consists in the construction pulsograms according to the results of counting the frequency of heart contractions in 10-second or minute recording segments. The method of statistical analysis of pulse intervals with the calculation of the mean values of the root-mean-square deviations of the variation factor and the autocorrelation function is more exact. The determination of the degree of pulse arrhythmia (the difference between the maximum and minimum pulse intervals in a given time interval) has an important diagnostic value. In particular, with the aid of precisely this method it was established that pulse fluctuation increases in weightlessness. This fact served as an impetus for the development of new methods of pulse analysis.

In cooperation with K. I. Zhukov, we developed the procedures of variational pulsometry.

We used the property of ergodicity of a dynamic number of pulse intervals in an investigation under relatively constant conditions (for instance, within the limits of a telemetry communications period).

Variational pulsometry is the calculation of the distribution segments of values of pulse intervals with the construction of variational curves or histograms.

To obtain a sufficient amount of numbers in each segment of the variational curve it is necessary to have no less than 100-150 values of the analyzed magnitude. In pulse analysis this is a 1.5-2 minute continuous recording. The interval between segments was selected as 0.05 or 0.1 sec, proceeding from the accuracy of recording calculations and the lower boundary of the normal limit of respiratory oscillations, the heart rhythm in humans 0.10 and in animals 0.15 sec. Variational curves make it possible to estimate the average pulse rate and fluctuation and the character of the transition processes in the various reactions of the circulatory system.

Figure 59B illustrates variational pulsograms of a healthy man under conditions of normal activity after physical exercise and while asleep. As can be seen, the sympathetic response (physical exercise) is accompanied by a shift of the variational curve to the left and pointing upwards (a decrease in pulse fluctuation);

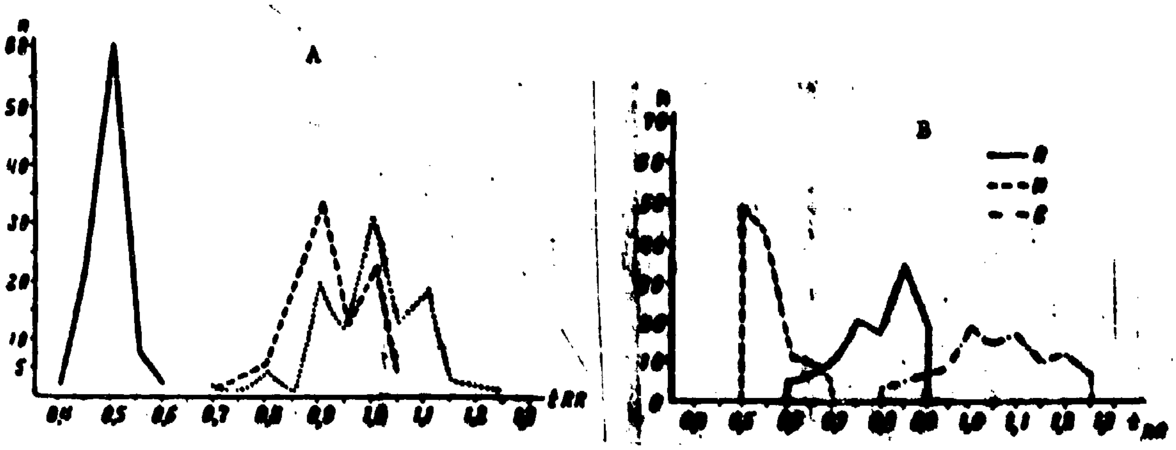

Fig. 59. Variational pulsograms. A — in the space flight of astronaut V. F. Bykovskiy (designated by dots). For comparison, pulsograms are given which were obtained during tests on Earth and in the pre-launch period (solid line and dotted line) B — on the ground for a healthy man at rest (П), after exercise (Н) and, a sleep (C).

the parasympathetic response (sleep), conversely, causes opposite changes: a shift to the right and flattening. Thus, the variational curve makes it possible to evaluate the state of neuro-endocrine regulation of the cardiovascular apparatus.

Figure 59 shows the variational curves of astronaut V. F. Bykovskiy during ground investigations in a spacecraft mockup in the pre-launch period (5 minutes before launching) and in weightlessness (71st revolution). Here it is distinctly determined that in the pre-launch period the tonus of the sympathetic nervous system sharply increases, while in weightlessness, there is observed a certain predominance of the parasympathetic system.

Variational pulsometry has permitted us to make important conclusions concerning the state of nervous regulation of the heart in space flight, and its application in space cardiology is very promising. This method is convenient for malifestation of slow rhythms of the vegetative nervous system, which is recently being given an important value [96, 652, 715].

Phonocardiography

Phonocardiography is the recording of the sound phenomena produced by heart activity. The sounds produced by the heart are characterized by a definite frequency spectrum and energy (intensity). Sound phenomena during auscultation are evaluated as tones or noises. The spectrum of heart tones lies within limits of 30-150 cps, and the noise spectrum is up to 800 cps (259).

A characteristic property of heart sounds is the unequal distribution of energy

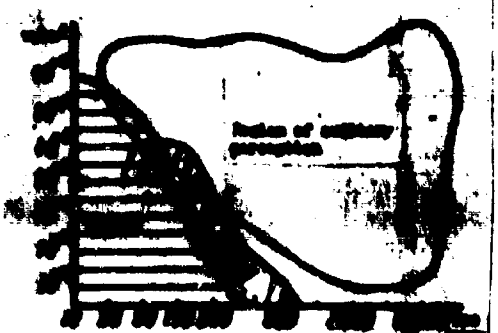

Fig. 60. Distribution of energy of heart vibrations and sounds depending upon frequency. Along the vertical – intensity of vibrations and sounds in w/cm^2; along the horizontal – on logarithmic frequency scale.

with respect to frequencies. As the frequency increases, the energy decreases (Fig. 60). More than 95% of the sound energy occurs in a range of up to 100 cps and only 5% occurs in the rest of the spectrum range up to 800 cps. However, sound energy composes only a small part of the mechanical energy of heart contraction.

A normal phonocardiogram consists of two tones – the first and the second (systolic and diastolic). The third and fourth tones are rarely observed.

The first tone is caused by tension of the myocardium and the walls of large vessels and by flapping of the atrioventricular valves in the beginning of the isometric phase.

The second tone is brought about by rapid flapping of the semilunar valves of the aorta and the pulmonary artery followed by opening of the atrioventricular valves.

In the investigation of healthy persons, e.g., in sports medicine, prime attention is allotted to such phonocardiogram characteristics as duration and amplitude of tones [109]. An important value is given in the clinic to phonocardiographic investigation of heart noises.

The value of the phonocardiographic method in cardiological examination consists in the possibility of objectively recording the force of the sounds, their phase relationships, and a number of time characteristics of the heart cycle [174, 222, 259].

Phonocardiogram recording under conditions of space flight has two purposes: to monitor the mechanical activity of the cardiac muscle and to investigate the dynamics of sound phenomena during the action of space flight factors. Considering that astronauts are specially selected and trained individuals who have no pathological heart murmurs, it is expedient to give prime attention to the recording of heart tones. In addition, inasmuch as phonocardiogram recording is impossible under conditions of the action of G-loads and vibrations, and also when conducting radio communications and in the process of activity, it is desirable to limit the frequency band when recording phonocardiograms in space flight. Limitation of the

frequency band has its advantages from the point of view of telemetry specialists since it makes it possible to significantly decrease channel capacity.

In reference to the conditions of the flight experiment on the second and third Soviet orbital spacecraft, we developed a special method called "integral phonocardiography" [29]. It consists of isolating a low-frequency envelope of audio-frequencies by means of detecting and integrating the output signals of a phonocardiographic amplifier. There is no information on the frequency composition of the phonocardiographic curve in this case, but it is possible to determine all the indices which characterize the energy and duration of heart tones. The transmission of an "integral" curve can be done by using telemetry channels with a considerably smaller capacity than that required or the transmission of the usual phonocardiogram.

As it is known, the designing of microphones with appropriate frequency characteristics for purposes of phonocardiography is being allotted considerable attention [141, 246]. The recording of "integral" phonocardiograms does not require special microphones. Practically any converter can be used which changes sound vibrations into voltage, including miniature telephones. This essentially facilitates sensor arrangement and attachment.

We used a miniature [TG-7] (ТГ-7) telephone (a 50-ohm resistor) without any special design modifications, and an amplifier with a gain factor of about 20,000 and a frequency band of 50-500 cps. We connected a diode detector and an integrating circuit with a time constant of the order of 0.02-0.05 sec to the amplifier output (a 2000-ohm resistor and a 20-microfarad capacitor). Figure 61 illustrates synchronously recorded regular and "integral" phonocardiograms.

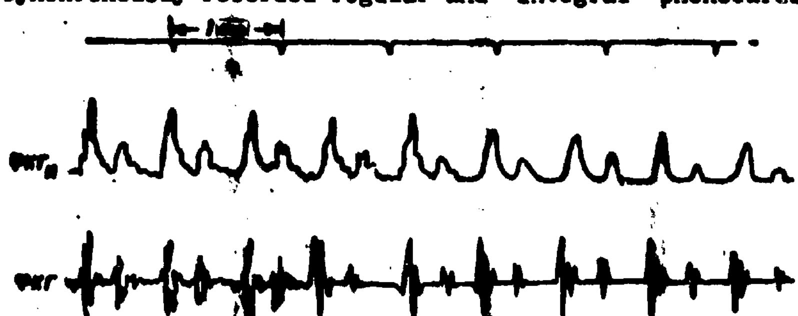

Fig. 61. A regular (ФКГ) and an integral ($ФКГ_u$) phonocardiogram.

It is interesting to note that in 1962 the United States published a patent for an analogous "integral" phonocardiography method for recording heart noises in limited frequency ranges [707]. Corresponding filters, a detector, and an

inertial recorder were used.

The method of "integral" phonocardiography was successfully used in flight experiments with animals. Phonocardiograms were recorded simultaneously with electrocardiograms. A pickup was attached in the region of the fourth and fifth intercostal space 2-4 cm outwards from the left edge of the sternum or above the apex. The pickup was attached to the animal with the aid of bandages. The pickup was mounted in an orlon case and was covered by a thin rubber band. This facilitated its attachment and did not cause skin abrasion when located on the animal for an extended period of time.

During the analysis of phonocardiograms we determined the following indices: amplitude and duration of first tone (I and t I); amplitude and duration of second tone (II and t II); duration of mechanical systole – time from beginning of first tone to beginning of second tone (t I, II); ratio of intensities of tones I and II (I/II); an electromechanical coefficient which determines the relationship of the duration of the electrical and mechanical systole ($K = \frac{t\ I,\ II}{t\ Q\ T}$).

Table 21 gives the values of normal variations of phonocardiogram indices in dogs which were obtained with the use of the described method. These data hardly differ from the results of phonocardiogram analysis in healthy dogs which were published by Yu. P. Antipchuk [19].

Table 21. Normal Values of Phonocardiogram Indices in Dogs

Index	K	I/II	t I, sec	t II, sec	t III, sec
Maximum value	1	2.5	0.15	0.09	0.28
Minimum value	0.7	1.2	0.08	0.04	0.19

The quality of the phonocardiograms that were obtained under conditions of orbital flight was quite high. In the powered phase it was possible to analyze only separate elements of the curve.

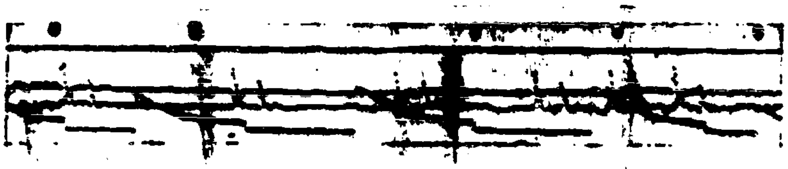

Fig. 62. Phonocardiogram of the dog "Belka" during orbital flight. Upper recording – integral electrocardiogram; lower recording – contact respiratory sensor.

Figure 62 illustrates the phonocardiogram of the dog Belka which was obtained during the circumterrestrial flight of the second orbital spacecraft.

Seismocardiography

The electrical and sound phenomena which accompany heart contraction do not provide a presentation on the final results of heart activity or with what force, regularity, and speed is blood pumped from the ventricles into large arterial trunks, and how filling of the heart occurs during diastoles. One of the methods which makes it possible to investigate these questions is ballistocardiography; however, its application under conditions of space flight is practically impossible. Therefore, with the cooperation of L. A. Kazar'yan, we developed a special modification of ballistocardiography called seismocardiography [39]. It is essentially the recording of the third and fourth derivative of the dorsoventral (or longitudinal) pectoral ballistocardiogram [190]. The principle of the method is based on the conversion of pulse motions of the chest wall into oscillations of an inert (seismic) mass which is elastically coupled to the subject of measurement. The seismic mass has a natural frequency of oscillations which lies beyond the range of cardiac vibrations. It should be noted that an analogous principle of recording mechanical oscillations of cardiac origin has been used in ballistocardiography [39, 186] and in kinetocardiography.

Several versions of seismocardiographic pickups have been developed. The first type of pickup was developed jointly with engineer L. A. Kazar'yan [28]. A drawing of this pickup is illustrated in Fig. 63. The pickup is intended for investigations on animals and was used during the flight of the third Soviet orbital spacecraft. The pickup consists of a metallic box with the dimensions 60 × 50 × 20 mm and a base made from laminated insulation to which a flat spring with a seismic mass, which is simultaneously the magnetic element of the conversion system, is attached. The second element of this system consists of two induction coils with iron cores, which are attached to the base of the pickup and are stationary relative to the moving seismic mass, i.e., magnet.

The pickup is placed on the back of the animal. Body motions that are brought about by heart contractions cause translocations of the pickup housing relative to the seismic mass. As a result of the action of inertial forces, the spring is strained and natural damped oscillations of the seismic mass occur. The frequency of the natural oscillations is 20-39 cps. The damping time is less

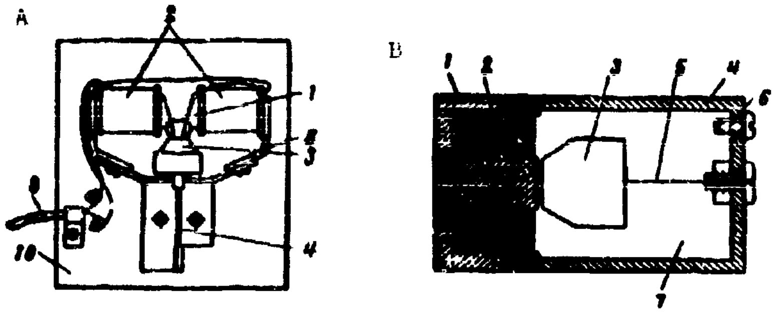

Fig. 63. Two samples of seismocardiographic pickup designs. 1 — steel core; 2 — coil; 3 — magnet-seismic mass; 4 — plastic housing; 5 — spring (steel string or plate); 6 — hermetically sealed holes for pouring in damping fluid; 7 — pickup cavity; 8 — magnetic wire; 9 — wire to amplifier; 10 — mounting plate; A) pickup used to study the dog Pchelka in space flight; B) modernized pickup.

than 0.1 sec. Thus, each pulse translocation of the body is accompanied by a cycle of natural oscillations of the seismic mass and the appearance of electrical voltages at the pickup's output. The amplitude and duration of every oscillatory cycle, other things being equal, depend on the magnitude of the acceleration acting upon the pickup and upon the time of its action.

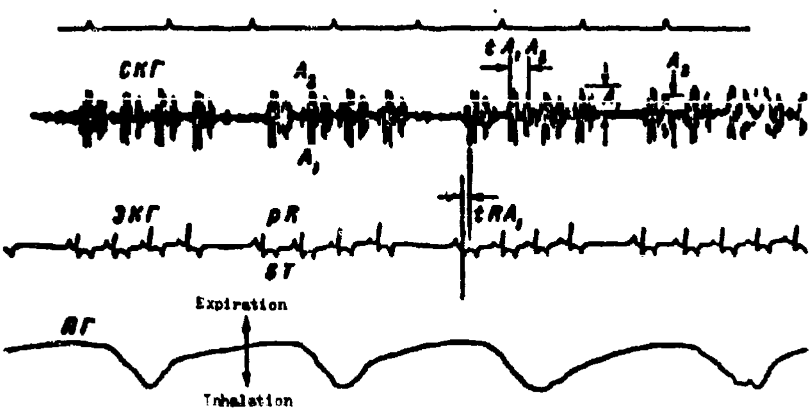

Fig. 64. Synchronous recording of a seismocardiogram (СКГ) and an electrocardiogram (ЭКГ). A pneumogram (ПГ) is shown at the bottom.

Figure 64 illustrates the synchronous recording of a seismocardiogram and an electrocardiogram. As can be seen, the seismocardiographic complex consists of two clearly determined parts (cycles): the systolic and the diastolic. The amplitude of each cycle is directly related to the magnitude of the forces acting in a given phase of heart contraction. The duration of the damping period depends

on the time relationships between these forces. The fact is that at each moment not one, but several forces act synchronously. If the normal synchronism of forces is modified, i.e., definite forces appear with a longer than usual time interval relative to each other, the damping period of the natural oscillations of the seismic mass should be increased. This will occur because the appearance of new inertial forces will cause out-of-turn vibrations of the body, which will lead to an increase in the time of damping the oscillations of the seismic mass. Thus, there can occur even merging of two cycles into one, or there may appear new brief oscillatory cycles (such phenomena were detected on seismocardiograms of cardiac patients).

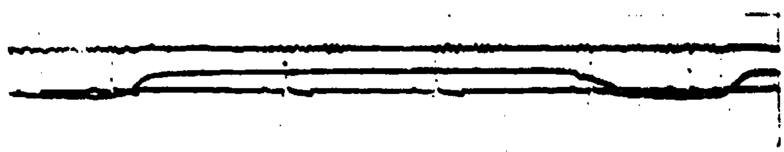

Fig. 65. Seismocardiogram recorded during flight of dog "Pchelka" 2/1/60. From top to bottom: seismocardiogram, pneumogram, and electrocardiogram.

During the analysis of seismocardiograms the following indices are usually determined: amplitude of the first (systolic) oscillatory cycle, which reflects the magnitude of cardiac forces acting in the systolic period (A-1); amplitude of the second (diastolic) oscillatory cycle, which reflects the magnitude of cardiac forces acting in the diastolic period (A-2); duration of the first oscillatory cycle, which determines the synchronism of the cardiac forces in the systolic period (t A-1); duration of the second oscillatory cycle, which determines the synchronism of cardiac forces in the diastolic period (t A-2); duration of mechanical systole (time from the beginning of the first to the beginning of the second oscillatory cycle) (t A1A2); of the electrocardiogram Q wave to the beginning of A-1 (t Q A-1).

Table 22 gives the values of some of these indices which were observed in dogs while lying on their stomach.

Table 22. Normal Values of Seismocardiogram Indices of a Dog

Index	A1/A2	tA 1, sec	tA 2, sec	tA 1A2, sec
Maximum value	2.0	0.20	0.12	0.29
Minimum value	0.5	0.12	0.08	0.17

In view of the fact that the frequency of natural oscillations of the seismic mass is sufficiently high, respiratory motions and other slow movements of the body practically do not influence the recording, there are only respiratory variations in the recording amplitude. Since the spring system of the pickup has only one degree of freedom, only movements in one direction are recorded. High-quality recordings are obtained, as a rule, only under conditions of complete rest of the investigated animal. During movement seismocardiogram recording is impossible, and the pickup works as an actograph. However, rapid damping of natural oscillations of the seismo-pickup makes it possible to record normal seismocardiographic complexes in the rest period between movements. It should be noted that also when recording under conditions of complete rest the sensitive seismo-pickup detects a certain oscillatory background caused by the presence of microvibrations of the body, which is related to the biophysical fundamentals of heat-regulation in warm-blooded animals [677]. Figure 65 shows a seismocardiogram that was recorded during the space flight of the dog Pchelka. In each recording period the clearest and most expressed complexes were selected. In view of the movements of the animal, a considerable portion of the recording is an actogram; however, it was possible to select no less than 15-20 complexes per recording period, which is quite sufficient for a statistical evaluation. Both the time and amplitude indices have fully reliable values inasmuch the construction of the seismo-pickup anticipates rigid attachment of sensors during the entire time of flight.

Two other types of seismocardiographic pickups were developed for human research.

The first one is a variation of the pickup that was used in experiments with animals. This pickup was also developed with the cooperation of L. A. Kazar'yan, and then manufactured by the "ЭМА" [EMA] plant. Normal seismocardiogram variations were studied by examining 20 young persons between ages of 20 and 22 years [37]. Seismocardiograms were recorded from various points of the anterior surface of the chest wall in the sitting and prone positions. An electrocardiogram and an pneumogram were simultaneously recorded. The pickup was arranged in such a manner that the direction of oscillations of the seismic mass coincided with the dorso-ventral axis of the chest wall. The pickup was secured with the aid of a rubber belt.

As a result of a comparison with other curves, it was established that the beginning of the oscillatory cycle A-1 corresponds to the beginning of the phase of rapid expulsion, and cycle A-2 is evidently connected with the forces which develop in the return blood stream in the aorta and the pulmonary artery, and partially with

the forces which appearing during rapid filling of the ventricles.

The time interval tA1A2 is practically equal to the duration of the mechanical systole since the first cycle starts in the middle of the isometric tension phase, when mechanical displacement of the ventricles occurs.

The results of the statistical processing of 20 seismocardiograms are given in Table 23.

Table 23. Normal Seismocardiogram Variations in a Human

Statistical index	Seismocardiogram indices							
	t Q A1 sec	tA 1A2 sec	tA 1 sec	tA 2 sec	A1, mm	A2, mm	A1/A2	$\frac{tA\ 1A2}{t\ Q\ T}$
Arithmetic mean (M)....	0.10	0.31	0.17	0.14	20.4	15.4	1.32	0.83
Standard deviation (σ).	0.025	0.033	0.047	0.03[illegible]	3.26	5.0	0.54	0.22
Arithmetic mean error (m)................	0.005	0.007	0.009	0.006	0.66	1.0	0.11	0.045
Variation factor (V)...	25%	10%	27%	22%	16%	32%	40%	27%
Maximum value (X_{max})...	0.128	0.38	0.24	0.18	28.7	19.8	3.05	0.93
Minimum value (X_{min})...	0.040	0.27	0.12	0.08	12.9	8.3	0.76	0.75

Another type of seismocardiographic pickup was developed at our suggestion by N. G. Esaulov (Fig. 66). This pickup was used in miniature form for research during the flight of the "Vostok-5" and "Vostok-6." Figure 67 illustrates the simultaneous recording of seismocardiograms with the aid of a miniature pickup designed N. G. Esaulov and a pickup manufactured by the "EMA" plant. As can be seen, there is a distinction only in the duration of damping the natural oscillations of the seismic mass, which is caused by the different degree of elasticity of suspensions and the different degree of damping (N. G. Esaulov's pickup employs oil damping).

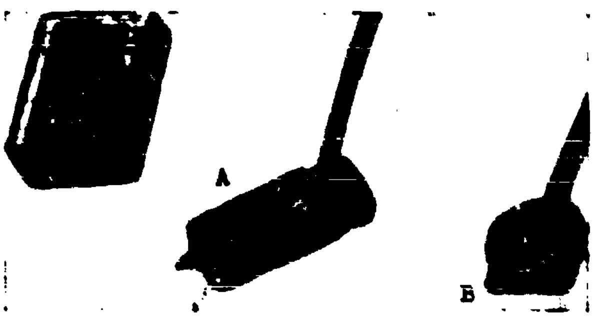

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Fig. 66. External appearance of seismocardiographic pickups. A – pickup whose drawing is shown in Fig. 64b; B – pickup designed by N. G. Esaulov.

Fig. 67. Seismocardiograms recorded by "EMA" plant pickups (A) and N. G. Esaulov's pickup (B). Electrocardiogram at top.

As indicated by Yu. N. Volkov's investigations (S. M. Kirov VMOLA), which were conducted at our suggestion, seismocardiography is a very effective diagnostic method in the clinic. Figure 68 shows seismocardiograms of different patients. These recordings illustrate the peculiarities of seismocardiograms for heart failure, myocardial infarction and arrhythmia.

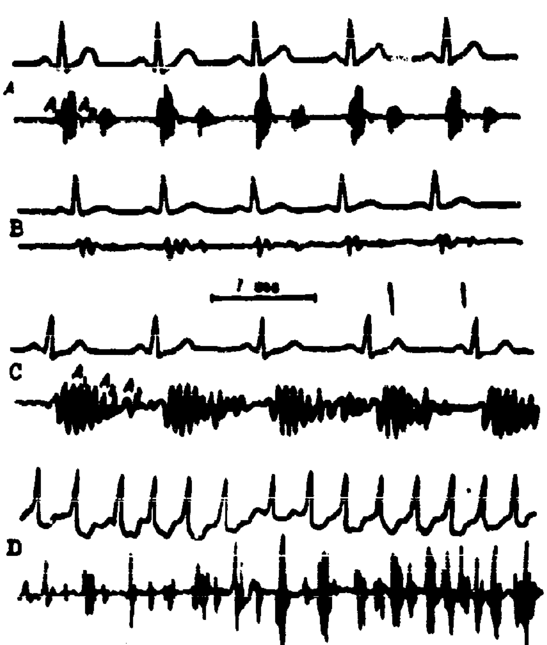


Fig. 68. Seismocardiograms recorded in a healthy individual (A) and in patients with arteriosclerotic cardiosclerosis (B), decompensated mitral valve failure (C), and paroxysmal tachycardia (D).

The application of the seismocardiography method in the "Vostok-5" and "Vostok-6" flights was an important stage in research on the influence of weightlessness on the human circulatory system. The pickup was placed in the region of the sternum and attached to the clothing from the inside. Seismograms were recorded on one telemetry channel with an electrooculogram. This was possible in view of the different frequency spectra of the processes which, in actuality, influenced the amplitudes of the seismocardiograms in the process of flight (see below).

However, neither the amplitude nore the time intervals changed. Figure 69 gives a sample seismocardiogram of V. F. Bykovskiy which

was obtained in flight.

During the flight of the "Voskhod," seismocardiograms were recorded simultaneously in all three members of the crew. The seismocardiograms were transmitted on one channel with pneumogram.

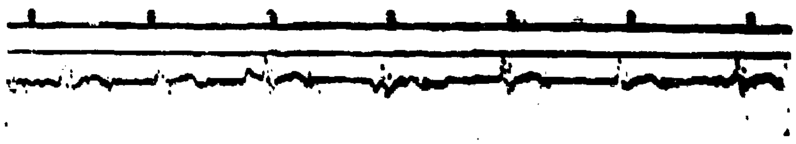


Fig. 69. Sample of V. F. Bykovskiy's seismocardiogram recorded in space flight.

Kinetocardiography

Kinetocardiography is the method of recording the local low-frequency vibrations of the chest wall. The method was developed by Eddleman and his associates [410, 411]. Kinetocardiography is one of the methods of seismic pectoral ballistocardiography [190] and makes it possible fundamentally to study the time responses of phases of the heart cycle [17, 685]. Comparative investigations showed that the kinetocardiogram both in form and in the information which it contains is very similar to electrokymography [748], ultralow-frequency ballistocardiography [684], and dynamocardiography [190]. During G. S. Titov's flight, kinetocardiograms were recorded by means of a pickup in the form of a miniature microphone with a preamplifier operating on one transistor (developed by I. S. Shadrintsev). The pickup was placed in the region of the apex beat and attached to the inside of a chest harness. Vibrations of the chest wall were recorded in a frequency range 10-20 cps. Figure 70 illustrates a kinetocardiogram that was recorded with the aid of the indicated pickup on G. S. Titov during flight.

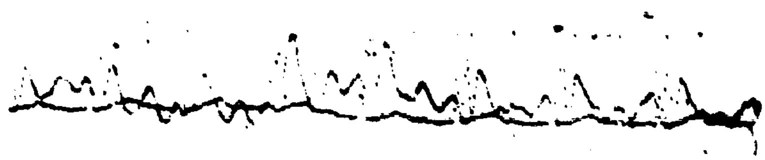
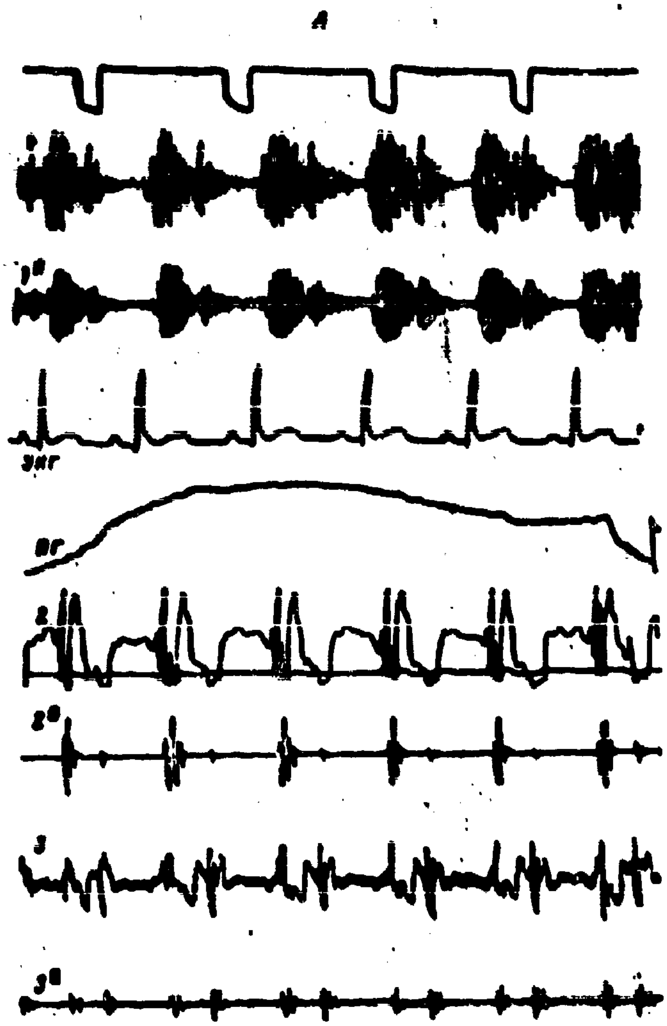


Fig. 70. Kinetocardiogram recorded during G. S. Titov's flight.

The disadvantages of the electromagnetic pickup are low sensitivity and the impossibility of recording vibrations in a region of frequencies of the order of 1-5 cps. Therefore, attempts were made to devise kinetocardiographic pickups on the basis of piezo-elements. One of the versions of this type of pickup is shown in Fig. 12. Work was later conducted on the miniaturization of this pickup with the use of piezoceramic elements. Figure 12

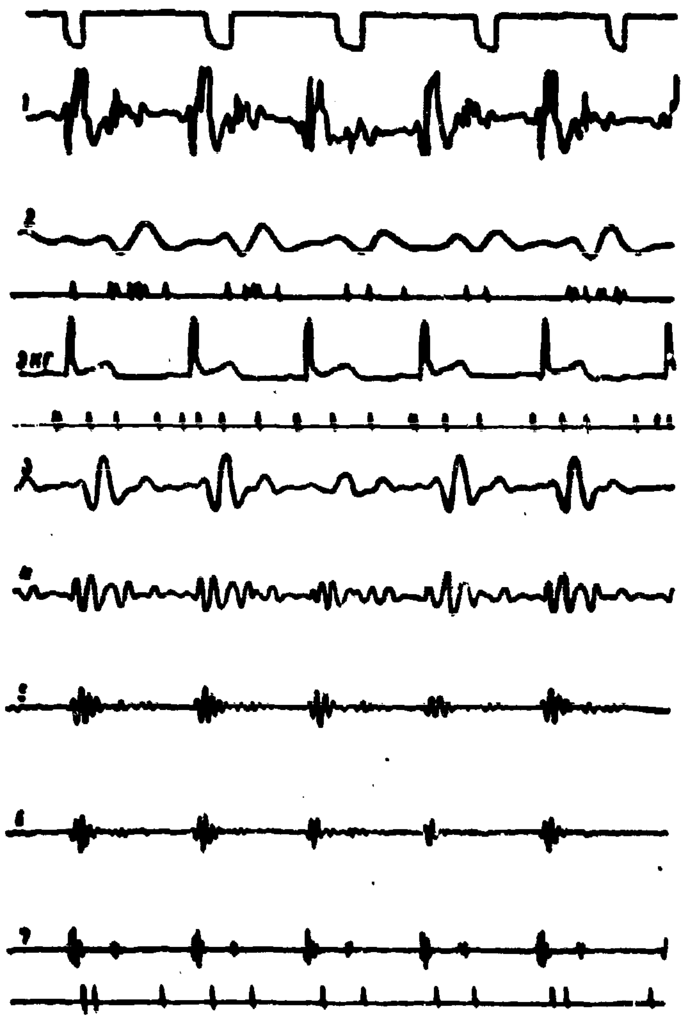
shows a piezoceramic pickup for kinetocardiogram recording (designed by V. I. Polyakov). This pickup provides an output signal of 1-2 millivolts in a frequency band from 1 to 40 cps (taking into account the characteristics of the entire recording channel). An important quality of piezoceramic pickups is their insensitivity to changes in humidity and temperature, their small-size, and sufficient mechanical strength.



71 A.

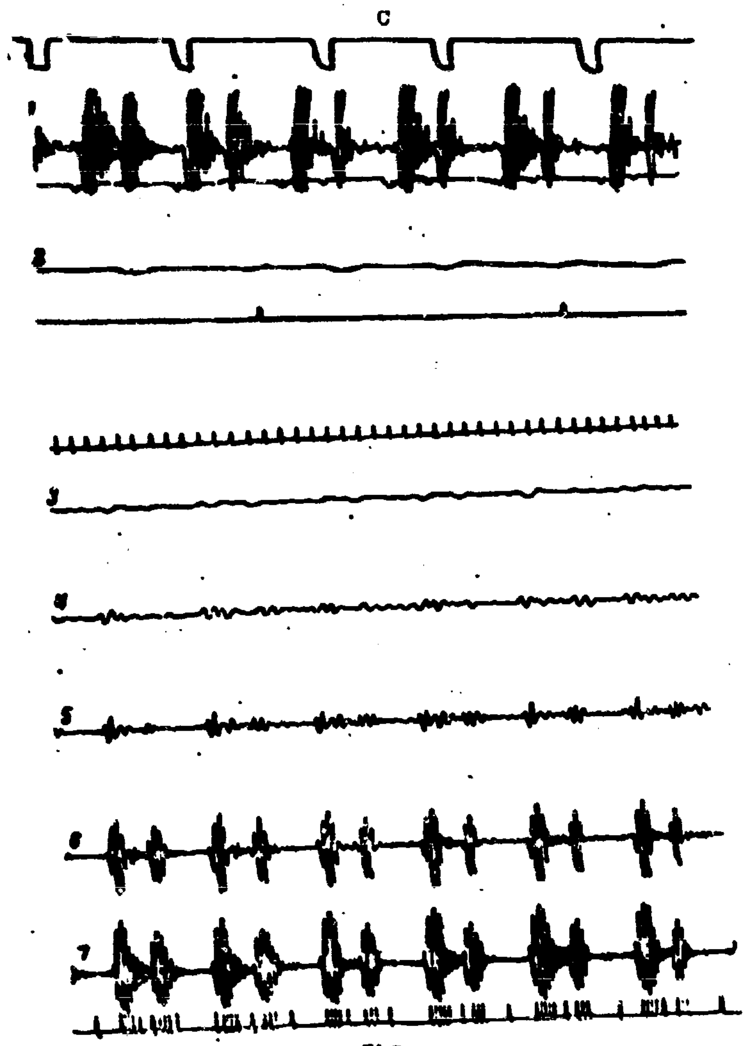
Fig. 71 (A, B, C). Seismo-kineto and phonocardiogram recording with the use of various filters. Figure 71A illustrates seismocardiogram (1), kinetocardiogram (2), and phonocardiogram (3) recordings, without a filter and with a filter, 25-40 cps (a).

B



71 B

Fig. 71B illustrates kinetocardiogram recordings (1) in frequency ranges 2-3 cps (2), 4-7 cps (3), 8-13 cps (4), 14-25 cps (5), 25-40 cps (6), and 40-60 cps (7).



71C

Fig. 71C illustrates seismogram recordings (1) in a frequency range of 2-3 cps (2), 4-7 cps (3), 8-13 cps (4), 14-25 cps (5), 25-40 cps (6), and 40-60 cps (7).

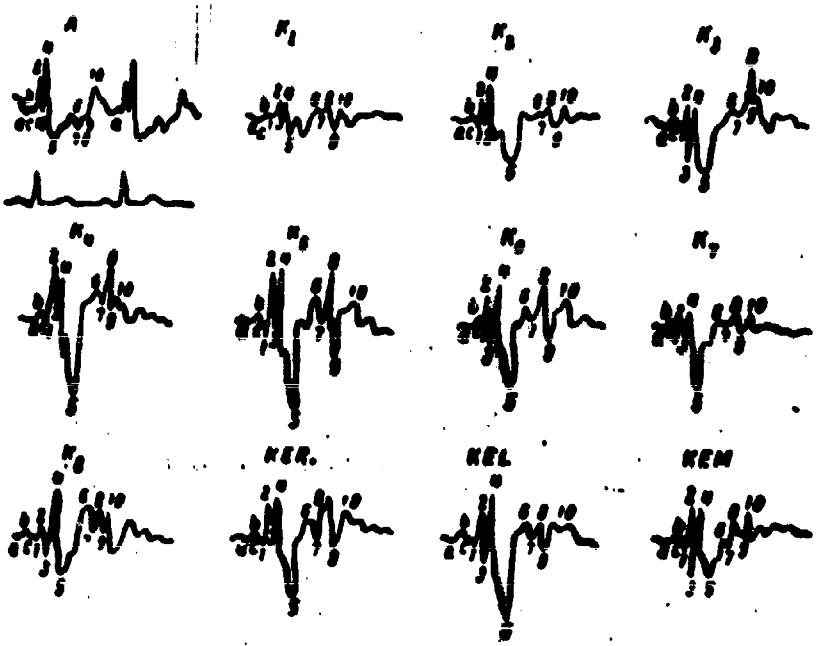


Fig. 72. Samples of kinetocardiograms recorded with the aid of a piezoceramic pickup in 12 positions. Figures designate kinetocardiogram waves according to L. B. Andreyev.

When considering the various pickup designs, one should note the significant relationship between the shape of the curve and the band of recorded frequencies [684, 685].

The illustrated curves (Fig. 71A, B, C) graphically demonstrate this relationship.

A kineto-pickup can be used to obtain recordings which are quite similar to seismo- and physiocardiogram recordings, especially when filters at frequencies above 15 cps are employed.

It is difficult to select points for attaching a kineto-pickup. As it is known, many different sites have been suggested for recording kinetocardiograms. Eddleman (1953) selected points which correspond to the 1-6 chest positions that are utilized in EKG research (these points are designated by the letter K with a figure indicating the number of the position), and also points in the epigastric region, in the center under the right and left costal arches (designated as KEM, KER, KEL). L. B. Andreyev [17] proposes four positions:

1) the fourth intercostal space near the right edge of the sternum (the site where the atrium dextrum is attached to the chest wall); 2) the point of intersection

of the anterior median line with the continuation of the fourth intercostal space (the sternum acts as a unique integrator of the activity of all sections of the heart); 3) the fourth intercostal space near the left edge of the sternum (the site where the right ventricle is attached to the anterior chest wall); 4) the region of the apex beat (left ventricle).

Figure 72 illustrates kinetocardiogram samples that were recorded with the aid of a piezoceramic pickup in all the indicated positions. Concise curves were obtained from points 2 and 4.

Because of the high sensitivity to the position of the pickup on the chest, kinetocardiography is not very suitable for investigations under conditions of space flight. This method is expedient to use for pre- and postflight examination of astronauts and in laboratory experiments.

Arterial Oscillography and Sphygmography

The measurement of arterial pressure and the study of pulse oscillations of the vascular walls pertain to traditional cardiological methods and are extremely important for evaluating the state of peripheral blood circulation under conditions of space flight.

There are direct and indirect methods for measuring arterial pressure. Direct methods, when the measuring instrument (manometer) is directly connected to the blood vessel through a cannula or a catheter (probe), are applicable only in critical experiments.

Indirect methods are suitable for the conditions of space flight.

The USSR has been employing the oscillographic method which was devised by Marey (1876). This method was subsequently improved by different authors. Considerable use has been obtained by the tacho-oscillographic method developed by N. N. Savitskiy. The methods of arterial oscillography are based on the recording of pressure oscillations in a cuff which constricts the vessel. In the case of tacho-oscillography the speed component of the oscillations is recorded. American space research has been using an audio method for determining arterial pressure. A special microphone is employed to record the sound phenomena that appear during the constriction of a vessel.

Arterial pressure was measured in animals by using a compression cuff placed on the carotid artery, which was exposed by a skin flap. Since the volume of cuff was small (about 3 cm^3), pressure was created in it by an automatic piston-type device.

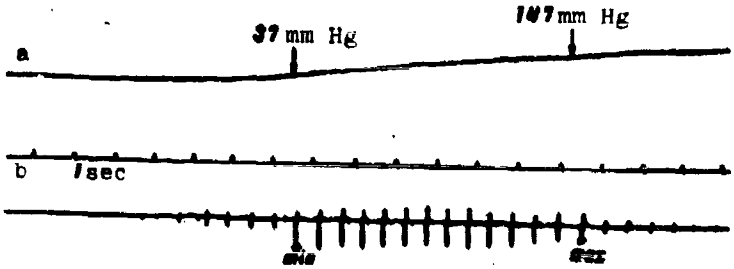


Fig. 73. Arterial pressure recording. a) pressure curve in cuff; b) timing; at the bottom is the oscillation curve.

Constructively, this device consists of a metallic cylinder with a carefully ground piston. The volume of the cylinder is calculated in such a manner so that a pressure of up to 220 mm Hg is created in the cuff per stroke. The piston moves in the cylinder under the action of a special cam which provides a slow (15-20 sec) build-up of pressure in the cuff and a fast (2-5 sec) drop in pressure. The cam is driven by an electric motor with a reduction gear. The influence of changes in pressure and temperature of ambient air is counteracted by a pneumatic valve which operates at a pressure of 220 mm Hg and removes pressure from the compression cuff regardless of the cam's position. The working cycle of the automatic pressure control was equal to 40 sec. This working cycle duration was selected from a calculation of the accuracy of the oscillator method (±5 mm Hg). At a minimum pulse rate of 60 per minute, there will be 40 oscillations on the recording in 40 sec, which corresponds to one oscillation per every 5 mm Hg. The pressure in the cuff varied linearly and was converted to voltage with the aid of an electrical micromanometer. Oscillations were recorded by means of a piezoelectric pickup and an amplifier (similar to the EKG type). Pressure and oscillation curves were recorded on different channels. Minimum and maximum arterial pressure were determined by marking points of the pressure curve which correspond to the moment of the beginning of the increase in the amplitude of the oscillations and the moment of the termination of the drop in their amplitude (73). The cuff was attached to the carotid by a special collar which was developed by O. G. Gozenko and A. A. Gyurdzhian [82]. A sensor and a micromanometer were attached to the collar.

Before a flight experiment could be conducted, special training with a skin flap exposing the carotid was required. Without training with the flap, the prolonged location of a cuff on it caused inflammation, traumatic damage to the skin, and abrasion. The training consisted of gradual increasing the duration of leaving a cuff on animals and the time of constricting the artery.

The training of an animal to wear a cuff has a known value in collecting sufficiently clear background data. Very high figures are usually obtained in the first pressure measurement, which is caused by the orientating, and sometimes the defensive, reaction of the animal.

The values of arterial pressure that are obtained by the oscillator method differs somewhat from the results of direct measurements [149] but can be fully used for a comparative evaluation. The values of maximum arterial pressure in animals which we obtained with the described method were within the limits of 80-130 mm Hg, while the minimum values were within the limits of 30-60 mm Hg.

Fig. 74. Measurement of arterial pressure in a finger. The amount of pressure is determined by the time of the beginning and end of the oscillations. Pressure builds up linearly in the cuff within the limits of 0-220 mm Hg.

For investigations of arterial pressure in humans, instruments with finger, shoulder, and hip cuffs were tested (Fig. 74). The values of arterial pressure in the digital arteries were very dynamic and depended on the position of the hand to a considerable extent. When the hand is raised, the pressure decreases; when the hand is lower, the pressure increases. Indeed, a similar phenomenon should not occur under conditions of weightlessness; however, it results in much inconvenience in all background recordings. An advantage of the digital method is the simplicity of the pickup, which is made in the shape of a ring. The entire procedure for measuring arterial pressure amounts to inserting a finger into the ring and turning on an automatic device.

During the "Voskhod" flight, the arterial pressure of the crew members was measured by a physician. He used a conventional tonometer. The cuff was placed on the shoulder. Maximum and minimum pressure was determined by listening to Korotkoff tones.

Arterial pressure in a human brachial artery was measured in the American "Mercury" space flights [788, 789]. A microphone was placed in the lower part of the cuff, which turned out to be very effective from the point of view of noise immunity and sensitivity of the measuring system [445].

In the first orbital flight of J. Glenn, there was no automatic pressure control and the astronaut pumped air into the cuff himself with the aid of a rubber

bulb located on his chest. Subsequent flights employed automatic pressure control. A pressure curve and an arterial phono-oscillogram were recorded on one telemetry channel.

The state of a vascular wall can be evaluated by oscillations or tones recorded in the process of measuring arterial pressure. Thus, the height of tacho-oscillogram waves characterizes the rate of change of the volume of an artery or tissue at the time of systole. Maximum oscillations appear when the pressure in the cuff is equal to the mean dynamic pressure in the artery. The amplitude of oscillations depends to a definite extent on the magnitude of arterial vascular tonus.

By measuring the time lag of the beginning of the oscillator wave with respect to the first tone of a phonocardiogram or, in an extreme case, to the R wave of an electrocardiogram, it is possible to investigate the speed of propagation of a pulse wave through elastic-type arteries. When a second cuff is placed on a limb farther away than the first, it is possible to measure the speed of the pulse wave through muscular arteries. American researchers made attempts to measure the speed of a pulse wave in a monkey during a flight experiment on a "Jupiter" ballistic rocket; however, information was not obtained through this measurement channel due to malfunctions in the equipment [449, 481].

All the mentioned methods for investigating a vascular wall are varieties of sphygmography, one of the oldest instrumentation methods of studying the circulatory system. The first instrument for recording arterial pulse, i.e., sphygmogram, was created in 1855 by Vierordt [131]. At present, many different kinds of pickups have been developed for converting the displacements of a vascular wall into electrical signals. Piezoelectric, tensometer, capacitative, and other pickups are being used.

In conjunction with V. I. Polyakov, we developed a method for recording sphygmograms in dogs [30], which was applied during the flight experiments on the fourth and fifth Soviet orbital spacecraft. The body of a cuff for measuring arterial pressure in the carotid was used as a pickup. A tensolite element (tube with carbon powder) or a piezo crystal was placed in the position of the rubber cuff.

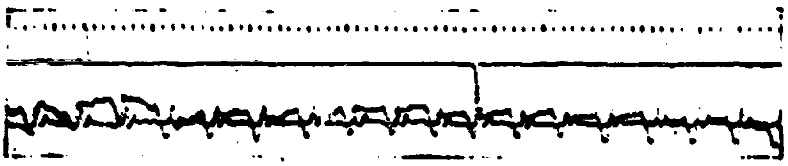


Fig. 75. Sphygmogram of the dog Chernushka in flight (electrocardiogram below).

The tensolite pickup had a voltage divider circuit. The separating capacitance together with the RC circuit form a simple low-frequency filter which limits the frequency band and thereby lowers the interference level. A filter in the form of a capacitance was used in the circuit with the piezo crystal.

Figure 75 illustrates a sphygmogram recording that was obtained under conditions of space flight. Due to the tight contact of the pickup's perceiving element with the vessel, cuff sphygmograph pickups give very stable recordings. Their quality is hardly influenced by animal movements and even vibrations.

The application arterial oscillography and sphygmograph made it possible to obtain preliminary data on the influence of weightlessness on peripheral blood circulation. A lowering of arterial pressure in the dog Strelka was detected in the beginning and at the end of flight [38]. Some hypotonia under conditions of weightlessness and after flight has been noted by American authors [550].

These data to a certain extent confirm the apprehensions with respect to the inclination towards an orthostatic collapse as a result of prolonged hypodynamia during submersion in water or under conditions of weightlessness [478, 479, 480, 550, 583, 584]. On the other hand, a lowering of arterial pressure can be the result of the "unloading reflex" which is caused by lowering the requirements of the cardiovascular system under conditions of weightlessness and by a certain increase in tonus of the vagus nerve [38, 270]. All this, in the end, indicates the necessity of developing special methods for investigating the peculiarities of peripheral blood circulation in flight, and especially vascular tonus.

Development of New Methods for Research on Circulation Under Space Flight Conditions

The significant achievements of space cardiology to a larger extent were brought abouty by the development of appropriate physiological methods and their application in flight experiments.

The data obtained made it possible to estimate basically the qualitative side of certain reactions of the cardiovascular system and also demonstrated the necessity of further development of cardiological methods.

Special attention is deserved by the study of the possibilities of evaluating the state of peripheral blood circulation since, with respect to cardiac activity, a definite amount of material has been accumulated, and a more detailed interpretation of it requires data on such important hemodynamic indices as the minute volume, the

mean dynamic pressure, and the peripheral resistance. In space flight it is possible to employ only indirect methods for determining these indices. Indeed, direct measurements in animals are possible with the aid of different types of pickups. American researchers plan to set up a special flight experiment to study the hemodynamic indices of primates [394]. They propose to record arterial and venous pressure, and the general work of the heart.

Hemodynamic research on humans under flight conditions is very difficult.

The separation of a medical research system for periodic recording of given parameters under conditions of rest facilitates the task to a certain extent. It is becoming possible to employ many methods which at present could not be used on a spaceship. The development of new methods is closely related to the creation of new radio-electronic equipment, new pickups, and the coordination of the obtained physiological information with the carrying capacity of the telemetry channels and the capacity of the memory units.

Let us consider certain methods that have been developed in reference to conditions of space flight or suitable for use on a spaceship without essential modification.

One of the promising methods of space cardiology obviously is electroplethysmography. An electroplethysmogram is a curve that deflects the oscillations of electrical resistance of tissues which are caused by translocations of the blood. Since the electrical conductivity of tissues is a little lower than that of the blood, the blood flow is accompanied by a decrease in its overall resistance and an increase in its shifting.

Electroplethysmography is known in two variations in the form of rheography, which was developed in 1945 by Poltzer, Marco, and Holtzer, and in the form of dielectrography, the authors of which are Atzler and Lehmann [1932].

In both cases the measurements are based on the application of high frequency, but rheography is used to investigate chiefly the changes in the ohmic component of the impedance of living tissues, and dielectrography is employed to study the capacitance component [144, 135, 178, 429].

The most effective is the application of electroplethysmography for research on cerebral blood circulation since under the influence of a modified gravitational field (G loads, weightlessness) there is observed a redistribution of the blood; the central nervous system can then be under unfavorable conditions. It is quite possible that the value of hemodynamic disorders in the brain for explaining

vestibular-vegetative disorders observed in different flights is minimized since there is no direct information on the state of the cerebral blood circulation under the conditions of outer space.

In 1961-1962, jointly with Yu. Ye. Moskalenko and O. G. Gazenko, we developed an electroplethysmography method in reference to research on cerebral blood circulation under the conditions of a modified gravitational field [180]. Intracranial electroplethysmograms were recorded in animals with the use of implanted electrodes. These electrodes are plexiglas plugs with a silver plate, and are screwed into trepanation holes until contact with the dura mater. Wires from the electrodes in polyethylene insulation are passed under the skin and drawn out on the back or occiput of the animal.

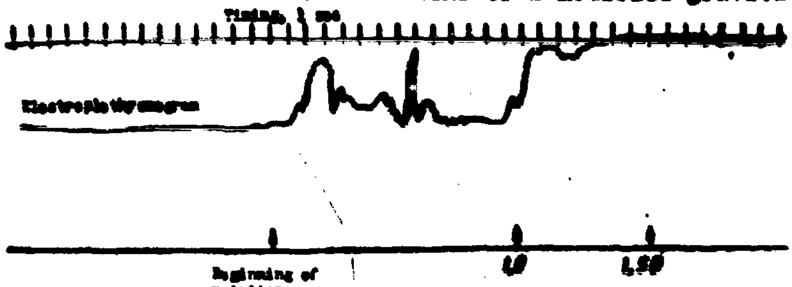


Fig. 76. Intracranial electroplethysmogram of a dog during the action of an overload along the "head-to-pelvis" axis (the magnitude of the overload in G's is shown on the bottom).

Intracranial electroplethysmograms were recorded with the use of a portable instrument designed by Yu. Ye. Moskalenko which was completely transistorized. Measurements were conducted at a frequency of 30 kilocycles with carrier amplification and signal detection at the output. The instrument recorded both slow and fast oscillations of resistance. Research was conducted on an intracranial electroplethysmogram of a dog during the action of an overload in the head-to-pelvis direction. Figure 76 shows the result of one of the experiments. As can be seen, from the beginning of rotation to the moment of achieving an overload equal to 1 G there were observed separate oscillations of intracranial impedance which, possibly, reflected the processes of the compensator adaptation of cerebral blood circulation to the action of accelerations. When the overload was increased above 1 G, a distinct growth in intracranial impedance was noted, which indicated a decrease in the blood supply to the cranium. Of interest is an electroplethysmogram of the head which was obtained by placing the electrodes on temporal regions [Fig. 77]. When the head is flexed, a decrease in resistance which corresponds to the flow of blood to the brain is noted. The value of rheography in research on cerebral blood circulation has been noted by many authors [147, 179, 545, 580, 589]; however, similar investigations in animals can also employ other methods: e.g., thermoelectric

methods with implanted thermoelements [140, 169, 556]. Electroplethysmography in a human is probably the only method of studying the blood supply to the brain which is applicable under conditions of space flight.

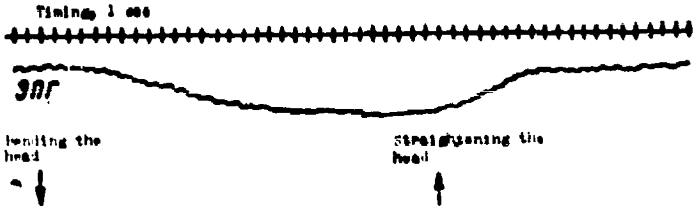


Fig. 77. Intracranial electroplethysmogram of a human during inclination and straightening of the head.

Valuable information can be obtained with the use of electroplethysmography for an analysis of peripheral blood circulation in the extremities. Various methods have been developed for studying arterial and venous circulation [61, 105, 668]. The possibilities of employing electroplethysmography for evaluating vascular tonus and arterial pressure are being investigated [402, 663, 555, 769].

According to Ye. G. Potapova, the application of rheovasography in pressure chamber tests has made it possible to detect curve changes in individuals with vegetative instability at altitudes of 2000 m, while no changes were detected on the part of the electrocardiogram or arterial pressure [212].

An important diagnostic value is given to pectoral and abdominal electroplethysmography [645]. In conjunction with A. Ye. Baykov, we developed a method of pectoral electroplethysmography with the use of additional electrodes mounted in the chest harness of an astronaut [see Fig. 51]. An instrument design by R. I. Utyamyshev was used, which recorded the fast (pulse) components of the electroplethysmogram in a frequency range of 0.5-40 cps.

The pectoral electroplethysmogram in the $C_2C_2^1$ lead has a rather complicated structure. It makes it possible to estimate the phases of the cardiac cycle, the speed of expulsion, and to indirectly judge the beat volume. A pectoral plethysmogram was recorded with the breath held at inhalation and expiration since the respiratory oscillations a few times exceed the pulse oscillations (Fig. 78). The same figure shows a volume kinetocardiogram that was obtained with the aid of a sensitive carbon pickup while the breath was held.

Pulse oscillations also can be recorded by measuring the oscillations of an air column in air passages. This method is called pulmocardiography. It was developed in the USSR by Ye. N. Luk'yanov [163]. Figure 79 shows a schematic pulmocardiogram together with a kinetocardiogram. As can be seen from the figure, the pulmocardiography method will make it possible to estimate the phases of the cardiac

cycle with sufficient accuracy. From the point of view of its operation, the pulmocardiograph is very suitable for application in medical research systems on a spaceship. To obtain a recording, it is necessary to place the mouthpiece of an air duct in the mouth and accomplish slow and smooth expiration through the air duct and the sensor cavity. The pulmocardiography sensor can be modified for complex measurement of parameters of heart activity, external respiration, and heat regulation (a thermistor is placed in the oral cavity).

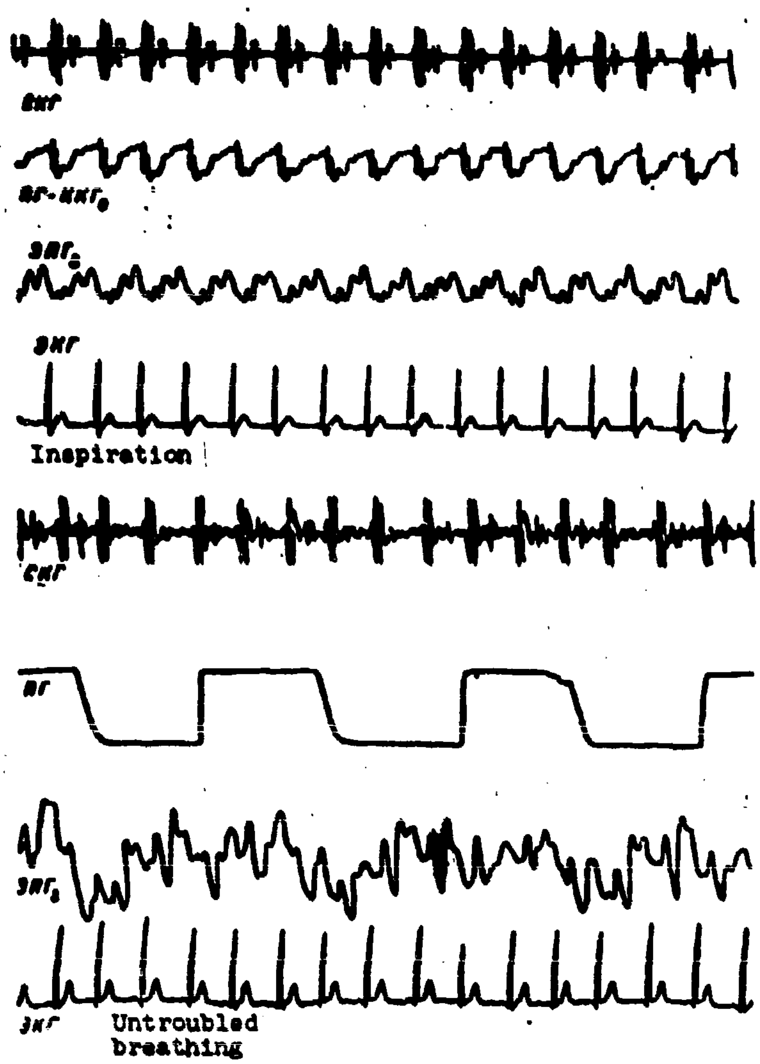


Fig. 78. Pectoral electroplethysmogram (ЭПГг) [EPG$_g$] during untroubled breathing and when holding the breath. ЭКГ) electrocardiogram; СКГ) seismocardiogram; ПГ) pneumogram. A carbon respiration sensor records the volume kinetocardiogram (ККГо) [KKGo] when the breath is held.

A large value is given to research on peripheral blood circulation. The development of the various methods and instruments for measuring arterial pressure in humans [482, 477, 108, 671, 538, 303] and in animals [422, 441, 127, 721, 666, 229] is the subject of a great deal of literature. Less attention is given to questions on the study of vascular tonus [91]. They are partially considered in monographs by V. V. Orlov [187] and N. I. Arinchin [21].

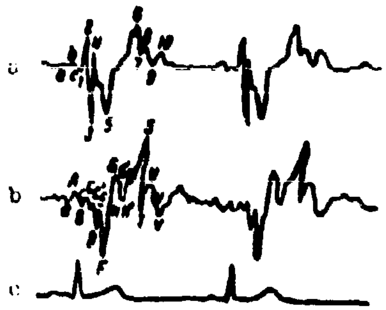


Fig. 79. Pulmocardiogram (b) synchronously recorded with a kinetocardiogram (a) and an electrocardiogram (c).

Special interest is aroused by the development of methods for studying the venous tonus of those regions where blood deposition is possible. One of the most accessible portions of the venous system for research is venous network of the lower extremities.

At the suggestion of A. M. Genin, we developed a measuring system for studying arterial pressure and vascular tonus of the lower extremities. The system includes a femoral compression cuff and a plethysmographic sensor which is placed on the knee. The femoral cuff is used to control the blood flow in the lower extremities and to measure arterial pressure. This is a simplified system in which only pulse oscillations of the plethysmographic curve are recorded. Vascular tonus is evaluated by the pressure difference in the first and second measurement [91] or by the difference in compression and decompression pressures [21].

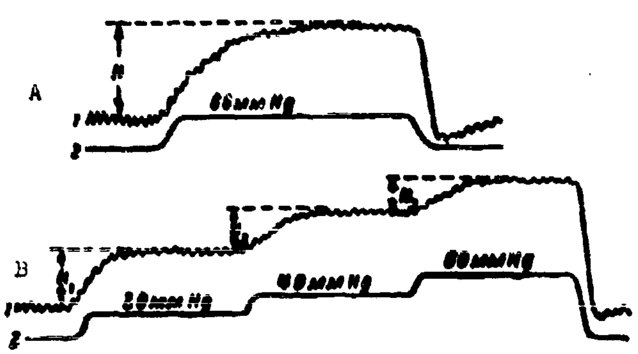


Fig. 80. Diagrams for determining venous tonus. A) measurement of the increase of volume (H) with the increase of pressure in the constriction cuff from 0 to 60 mm Hg; B) measurement of volume increases with the gradual increase of pressure; 1 – plethysmogram; 2 – pressure in cuff (according to V. V. Orlov).

A more detailed study of peripheral blood circulation involves the use of N. I. Arinchin's method. It makes it possible to evaluate the venous vascular tonus.

N. I. Arinchin's method [21] is based on the recording of volume changes of an extremity during a gradual increase of pressure in a cuff that is worn proximal to

the investigated portion. The measure of venous tonus in this case is the height to which the plethysmographic curve rises. However, the amount of blood contained by the venous reservoir, and consequently, the height of plethysmographic curve, depend on the rate of blood flow and the speed of constricting the arteries. Therefore, the more correct method is the one based on the rise of pressure to a specific magnitude, e.g., 40-60 mm Hg, and measurement of the maximum height to which the plethysmographic curve rises. According to available data, the maximum rise occurs 15-30 sec after the veins are constricted. The method of gradually increasing the pressure is even more exact. Here, the increase in the height of rise does not depend on the initial venous pressure (see Fig. 80).

CHAPTER 8

RESEARCH ON THE EXTERNAL RESPIRATORY FUNCTION

External respiration is the exchange of gaseous constituents between the external air and the blood in the pulmonary capillaries. Changes in the external respiratory function occur in various states which are involved both with changes in the gas composition of the external medium (an increase in the carbon dioxide content, a decrease in the oxygen content) and are also caused by pathological shifts as a result of extreme influences of various character (G-loads, hyperthermia). The function of the external respiratory system is closely related to the circulatory and heat-regulation systems, and also the central nervous system [106, 170].

The indices of external respiration can be divided into three groups [303]: 1) indices which characterize external respiration on the "external air-alveolar air" stage. The frequency and rhythm of respiration, lung volumes (vital capacity of lungs and others); 2) indices which characterize external respiration on the "alveolar air-blood in pulmonary capillaries" stage; composition of alveolar air, amount of oxygen absorbed, quantity of carbon dioxide eliminated, and others; 3) indices which characterize the gases in the arterial blood: the percent of oxygen saturation of the blood, its carbon dioxide content, and others.

It is very difficult to carry out a complicated sequence of functional investigations under the conditions of space flight especially those whose purpose is to study the indices of the second and third group. Therefore, prime attention is presently being given to the recording of external respiration indices which are related to the respiratory rate and rhythm and the lung volumes [106]. The following methods can be used for investigating the values of these indices:

a) pneumography — recording the changes in the chest perimeter [303, 629]; b) spirography — recording the volumes of inhaled and exhaled air [240, 260, 664]; c) pneumotachography — recording the changes in the rate of inhaled and exhaled air [165, 206, 348]; d) recording the changes in the intrapleural or intratracheal pressure [444]; e) recording the changes in electrical resistance of the chest (impedance pneumography) [444, 557]; f) recording the biopotentials of the respiratory muscles [275, 276, 426, 508, 535]; g) recording the mechanical translocations of the body that are caused by respiratory movements [39]; h) recording pressure oscillations related to respiration in a pressure chamber [319].

From the rather considerable number of methods it is possible to note those which are absolutely unacceptable for space flight conditions (g) and also those which are unsuitable for the investigation of humans, but can be used in experiments with animals (d). Many of the methods can be used with some modification for investigations on a spaceship.

Inasmuch as the main task in the first space flights was medical monitoring, respiration was recorded by the simplest method, i.e., pneumography. The shortcomings of the pneumographic method are well known: the impossibility of monitoring the depth of respiration, the significant dependence of the character of the recordings on the method of attaching the sensor, and the interference during pneumogram recording which is related to the movements of the subject and conversations.

In the process of preparation for the flight experiments on the "Vostoks" diverse variations of sensors for pneumography were tested, including sensors based on the piezoelectric effect, wire potentiometer, and tensometer circuits. All of them turned out to be unsuitable either because of their bulkiness or due to the necessity of creating a special measuring and amplifying circuit. From the point of view of simplicity and economy, the most useful device turned out to be a carbon sensor made in the form of a rubber tube filled with carbon (microphone) powder. In its nonexpanded state, this sensor has a resistance within the limits of 100-500 ohms. When expanded, its resistance is increased to several thousand ohms. Its sensitivity can reach over ten ohms per mm of movement. However, carbon sensors are nonlinear. Their sensitivity changes depending upon the magnitude of initial expansion (see Fig. 9). The suitability of these sensors for respiration recording is determined by the fact that pneumography practically investigates only the respiratory rate and rhythm, while the depth of respiration cannot be

recorded by this method. Thus, the nonlinearity of the carbon sensor does not prevent its application for pneumography.

To measure respiration under space flight conditions, the carbon sensor is attached to the chest harness in such a way that it expands together with the rubber inserts during respiration. The sensitivity of the sensor depends on the following methodological factors: selection of the site for attaching the sensor; elasticity of the rubber inserts; initial magnitude of expansion of the sensor.

It is clear that such phenomena as displacement of the harness in flight, weight loss and weight gain of the astronaut, and the pressure of the clothing or space suit on the sensor can lead to a lowering in the sensitivity of the sensor and even to a complete cessation of recording. Therefore, the careful installation and individual fitting of the respiration sensor take on an important value in the process of flight preparation.

Another type of sensor for pneumography is called the contact sensor. It is based on the closing and opening of an electrical circuit with the aid of a microswitch that is controlled by a caprone cable. The contact sensor is actuated every time the caprone cable changes the direction of its motion; the cable is attached to the chest harness at the end of the rubber insert opposite the sensor. Square pulses are recorded which correspond to inhalation and expiration. From the point of view of reliability, the contact sensor is preferable to the carbon sensor since its work is not distrubed when the initial tension of the harness is changed.

Both types of sensors were used in the "Vostok" flights. The carbon sensor operated with a transistorized amplifier that had an amplification factor of about 20 and a frequency range from 0.1 cps to 40 cps. This channel was connected to the main telemetry system and the on-board memory unit. The contact respiration sensor was used to monitor the respiratory rate in the decent phase after ejection. Recording was performed by a self-contained recorder which was located in the pilot's [NAZ] (HA3).* A sample of a respiration recording which was obtained with the aid of a monitoring sensor during the descent of astronaut P. R. Popovich is illustrated in Fig. 81.

*Tran. Ed. Note: This abbreviation is not explained in the text. It may possibly denote "automatic recording set" or "personal (individual) recording equipment."

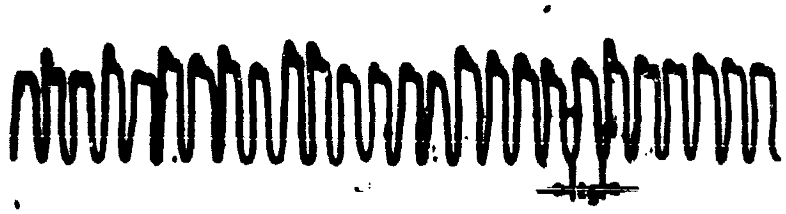


Fig. 81. Pneumogram recording by a contact sensor for astronaut P. R. Popovich during his parachute descent after ejecting from the spacecraft cabin (tg — duration of respiratory cycle).

On the pneumogram recorded by the carbon sensor it is easy to differentiate the respiratory motions from conversation and other motions (Fig. 82).

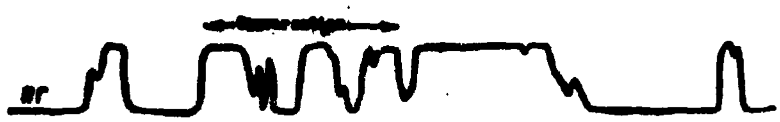


Fig. 82. Recording of a pneumogram [PG] (ПГ) during a conversation.

Recording of respiratory motions in animals was accomplished with the use of a special belt with tensolite and contact sensors. Elastic inserts were sewn into the belt in such a way that an increase of the perimeter of a dog's chest at inhalation and a decrease at expiration caused strengthening and weakening of the tension of a rubber tube containing carbon powder. When the belt was being designed, measures were taken to standardize the tube tension with the aid of a special functional diagram. The sensor was placed in a box made from organic glass. This increases the operational qualities of the sensor, facilitates its adjustment on the animal, and ensures the absence of distortions involved connected with the location of material over the sensor.

Of importance in the investigation of animals was the correct installation of the belt with the respiration sensor. Respiratory motions in dogs are the most expressed in the abdominal region. However, the installation of an abdominal belt is impossible due to impairment of the functional state of the animals when the abdominal organs are compressed. Therefore, the fitting of belts with respiration sensors required tedious work on the selection of the most successful sites for installing a belt in the sense of obtaining the highest recording amplitude. The necessity of obtaining a sufficiently high recording amplitude was caused by the fact that the tensolite sensor was included in the recording circuit without an

amplifying channel. Due to this, the sensitivity and frequency-response curve of the pneumogram-recording system were determined by the sensor and the telemetry system. It is interesting to consider certain indirect methods of monitoring and research on respiration on the basis of the results of telemetry measurements in flight.

An electrocardiogram is a good indicator of respiratory motions. Changes in the tonus of the vagus nerve during respiration lead to changes in the functions of automatism, excitability, and conduction. The duration of intervals is increased at inhalation. The respiratory arrhythmia is quite clear in dogs. In addition, the respiratory motions of the diaphragm affect the position of the heart in the chest. This leads to a change in amplitude of the electrocardiogram waves. For instance, in the 1st lead, at inhalation the R waves decrease, and increase at exhalation. The seismocardiogram also changes during respiration. At inhalation, due to the intensive flow of blood to the right ventricle, the speed of expulsion is increased and the amplitude of the first cycle is increased. The second cycle usually decreases due to blood deposition in the vascular channel of the lungs. The duration of oscillatory cycles also changes. Respiration also can be monitored according to other parameters: by a phonocardiogram, sphygmogram, or electromyogram.

American space research has been using different methods for recording respiration: pneumography (a rubber tube containing a copper sulfate solution), pheumotachography (a variation with a heated thermistor which is attached in the form of a microphone in the flow of exhaled air), and impedance pneumography (measurement of the electrical resistance of the chest).

The method of impedance pneumography was applied during the flights W. Schirra and G. Cooper [788]. According to American authors, the respiratory changes in impedance when the electrodes are placed in the 6th intercostal space on the left and on the right along the midclavicular line are directly proportional to the magnitude of pulmonary ventilation [557].

There is a report on a miniature impedance pneumograph to be placed the astronaut's clothing [632]; its size is 13 × 56 × 94 cm, and its weight is 125 g.

It is interesting to note that the American researchers have developed special barrage filters to decrease the number of electrodes on the astronaut's body; these filters permit the recording of an electrocardiogram and an impedance pneumogram from the same electrodes. The filters are tuned to the frequency of the

pneumograph oscillator and are connected at the input of the EKG amplifier [443].

The method of impedance pneumography has definite advantages over the other methods which donot involve the use of a mask in the sense of the possibility of a quantitative estimate of pulmonary ventilation; however, it is not suitable for prolonged investigations (see above).

The study of respiration in space flight according to pneumography data is of interest both to the physicians that monitor the astronaut's state in the course of a space flight and also to scientific research on the influence of flight factors on the respiratory system. From the point of view of monitoring, the very fact of the presence of respiration signals indicates the preservation of vital functions.

There is a report on the use of an "electronic attendant" instrument which monitors neonatal respiration and sends out a warning signal in the event of respiratory failure [412]. A special monitoring device, i.e., a self-contained respiratory recorder, which was actuated at the moment of capsule ejection, was employed during the animal flight on the second Soviet orbital spacecraft. This device was intended for accurately determining the moment of respiratory failure in the event of the appearance of any unforeseen extreme influences. As we know, Belka and Strelka were returned to Earth alive and unharmed, and the self-contained recorded played only a prophylactic role.

The respiratory responses during the action of accelerations make it possible to evaluate the state of animals or humans [686, 782], and they indicate the degree of adaptation of the organism under weightless conditions. This could indicate a possible decrease in pulmonary ventilation and metabolism; however, for such a conclusion necessitates more direct variations of the parameters of external respiration.

Two groups of instruments can be used to estimate the respiratory minute volume, the vital capacity of the lungs, the depth of inhalation, and other indices related to a change in the lung volumes; instruments which require the installation of a sensor in the flow of exhaled air and instruments which are not involved with this requirement. Instruments of the first group — spirographs and pneumotachographs — have obtained the widest application. Spirographs are designed with the use of the various principles of converting air volumes into electrical signals. One of the simple methods is the anemometric procedure: the exhaled air revolves a light-weight turbine which is connected to an electrical converter [256]. Figure 83 illustrates a sample of a spirogram that was recorded by an impeller

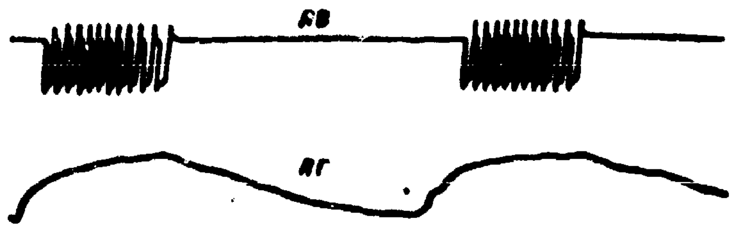


Fig. 83. Recording pulmonary ventilation with an anemometric impeller pickup [LV] (ЛВ) synchronously with a pneumogram [PG] (ПГ).

pickup designed by the SKTB [Special Technological Design Bureau] "Biofizpribor."

A pneumotachogram is obtained for recording the speed of the air flow. This method has many modifications and uses of different types of pickups. The universal pneumotachogram that is mass-produced by VNIIMIIO uses an optical recorder with a differential manometer, and its pickups consist of a hollow tube with a diaphragm or a cylinder with a plate that is mounted in the flow of air, which creates a certain resistance [206]. There also are pneumotachographs with electrical converters [348]. Bartlett [301] has proposed a new method for evaluating respiration by means of the speed-volume loop which is formed as a result sending signals from a pneumotachograph to an oscillograph screen (one directly from the instrument, another integrated). The method makes it possible to investigate numerous indices of external respiration. Clinical data indicate the diagnostic effectiveness of the method. The obtainment of a "volume-speed" loop requires a total of one telemetry channel since the volume curve can be synthesized from a pneumotachogram on Earth.

From the other methods of investigating external respiration, attention is deserved by the electromyographic methods. L. L. Shik [276] pointed out the presence of a dependence between the amplitude of currents of the action of intercostal muscles and the depth of inhalation. Many authors are using this method to monitor respiration in animals and humans [426, 508, 535].

Of special interest to space physiology are the possibilities of evaluating the indices which characterize the composition of inhaled and exhaled air and the gases in the arterial blood.

There are many bulky and complicated stationary instruments for evaluating the gas composition of exhaled air. Of the miniature instruments, the widest application has been obtained by instruments based on the ultrasonic method of determining carbon dioxide content [564, 737] and the polarographic method of determinating

oxygen content [742, 124]. An electrolytic method for determining oxygen consumption in small animals also has been developed [322]. Some application for measuring carbon dioxide has been obtained by pickups which operate on the principle of the difference in thermal conduction of air and carbon dioxide. The pickup consists of a balanced bridge made from heated platinum elements (resistors) placed on the ducts of exhaled air. The appearance of carbon dioxide causes disbalance of the bridge [89]. With an appropriate degree of heating the platinum elements, this bridge also can be applied for oxygen measurements. According to Visser [762], a pickup that is made from four platinum wires 6 cm long and 20 microns thick possesses a sensitivity of 0.1 mv per 1% of carbon dioxide when heated to 50°C and 1 mv per 1% of oxygen when heated to 400°C.

One of the possible variations of investigating the gas composition of air by means of taking samples followed by their analysis under laboratory conditions should also be pointed out.

Oxygen saturation of the blood under the conditions of space flight can be estimated by the oxyhemography method. This method was developed in the USSR by Ye. M. Kreps. The main component of the oxyhemometer is a pickup which is placed on the pinna. A beam of light which is passed through tissues and subjected to absorption and diffusion in them, strikes the light-sensitive layer of two photocells — "red" and "green".

The resultant photoelectric voltage is determined by the oxygen saturation of the blood, regardless its amount contained in the tissues [152]. This pickup can be independently attached for the period of medical research.

Recently there have appeared proposals with respect to the creation of combined instruments for simultaneously investigating a large number of indices of external respiration. One of these instruments makes it possible to record 11 different quantities. It consists of a pneumotachogram with an integrator, gas analyzer, and oxyhemograph [361]. A similar instrument with some modernization, e.g., the addition of heat pickups for measuring the temperature of exhaled air, could be used successfully in a space flight for fulfilling a specialized program of medical research on the external respiratory function (see Table 10).

Figure 84 illustrates a sample of the complex recording of a pneumogram and a seismocardiogram. This method was developed at our suggestion for application on the "Voskhod" for the purpose of a more economical use of the capacity of the telemetry links. In this case a common amplifier was employed for pneumography

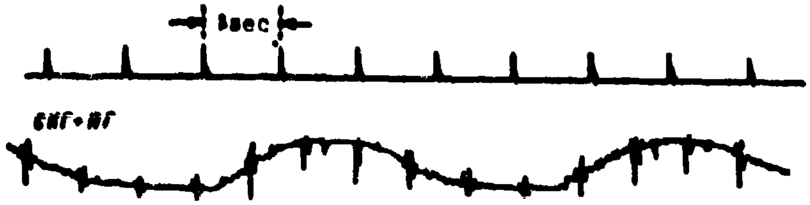


Fig. 84. Single-channel recording of a seismocardiogram and a pneumogram [SKG + PG] (СКГ + ПГ).

and seismocardiography, which is an example of the creation of a combined instrument.

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C H A P T E R 9

METHODS FOR STUDYING THE NEUROMUSCULAR SYSTEM AND WORKING CAPACITY

Research on the human working capacity is of paramount value for the solution of practical problems of astronautics. The questions of spacecraft control by a human operator can be solved only on the basis of the optimum selection of information characteristics of the "man-machine" system and the quarantee of the necessary coordination of voluntary motions. Motor acts are processes of the active influence of an organism on the surrounding world and each act is the solution (or an attempted solution) [46, 47] an action problem. An action problem a reflection of the "necessary future" which is coded in the nervous system. Thus, the purposeful activity of an astronaut in spacecraft control and the performance of natural and working acts, from the point of view of contemporary science, can be represented in the form of a series of realizations earlier programmed motor skills. A definite role is played by the processes of information perception, processing, and transmission on each stage of realization.

The information links between the astronaut and the spacecraft systems are of both scientific and practical interest. On the one hand, it is important to clarify the question concerning the influence of space flight factors on the various information processes. Thus, it is known that the zero-gravity state is accompanied by a lowering in the flow of afferent impulses. This circumstance is increased by hypodynamia and relative isolation. Information processing in the astronaut's central nervous system and the acts of realization of known motor skills also can change under the unusual conditions of space flight. The practical side of the matter in the final result involves the ability of the astronaut to perform purposeful actions and, in particular, to perform the control process.

Starting with the investigation of the simplest automated motor acts, which can be studied in animals, and ending with the solution of strictly "human" problems involved with the control of complicated systems, an important role is played by the single methodological approach in the sense of the physiological measurement of the information processes that take place in the single "man-machine" system.

The first flights positively answered only the question concerning the possibility of performing specific working operations under the conditions of space flight. The astronauts conducted radio communications, orientated their spacecraft, recorded this impressions in the flight log, and took care of their natural needs: all this indicates that the action of space flight factors does not cause essential disturbances in working capacity. But the question concerning the functional capabilities of the pilot-astronaut, his ability to perform certain specific operations, and fatigue requires further special research.

The ability to perform purposeful activity is closely related to the state of the nervous and muscular system. The first investigations of these systems were conducted during flight experiments with animals. The methods of actography and electromyography were used. Astronaut activity was subsequently evaluated by means of radio conversation materials, television data, analysis of recordings in the flight log, and others. An important method of investigating the state of the central nervous system was electroencephalography.

A new stage in physiological research on working capacity began with flight of the Soviet "Voskhod" spacecraft. A special method for providing a quantitative and qualitative calculation of specific astronaut activity (programmed research) was used for the first time. New methods which directly characterized working capacity and precise motor coordination were employed. Finally, the participation of a physician in the flight made it possible to give a medical evaluation of the astronaut's health, condition, and certain features of their activity in flight which could not be recorded objectively.

Actography

Actography is the method for studying motions. The motor activity of humans and animals appears in the form of coordinated and purposeful acts. Motion is one of the universal manifestations of the vital activity of humans and animals. Human motions reflect activity that involves work and contact with people, working

operations, professional skills, and also very precise spoken and written coordinations which occur on the basis of reflexes of the second signal system [48, 164].* Actography makes it possible to investigate motor activity in time. There is general and differential actography [303]. In general actography, motions are recorded regardless of to what they are related. Differential actography examines only specific special motions (e.g., the control process, writing, or moving the head).

Research on motor activity under space flight conditions can be conducted on the basis of television data and certain artifacts of a number of physiological recordings, e.g., electroencephalograms or seismocardiograms. A seismocardiographic pickup can be considered as an actograph. Under conditions of rest, it records body motions that are related to heart activity. During the motions, it provides information on the motor activity of the human or animal (Fig. 85).

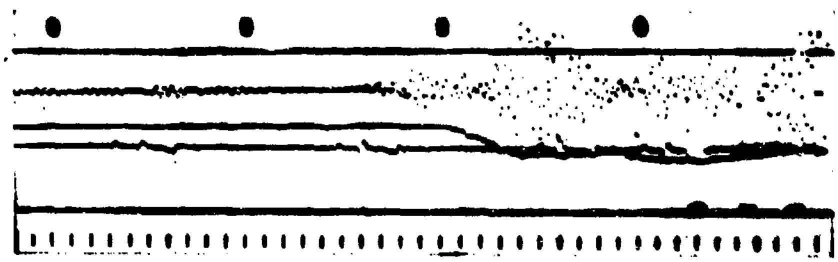

Fig. 85. Recording of motor activity by means of a seismocardiographic pickup (sample of a telemetry recording during the flight of the third Soviet orbital spacecraft). The dog "Pchelka."

The application of seismic pickups for investigating motor activity has been described by many authors. Cavagna, Saibene, and Margarita [379] described a three-directional accelerometer for analyzing body movements. It consists of a flat steel spring that is secured in a rigid frame. A small weight is attached in the center of the spring and tensometers are glued on both sides. A bridge circuit makes it possible to record a disbalance signal which is proportional to the acceleration. Three of those transducers make it possible to obtain a three-directional accelerogram. The size of the transducer block is 40 x 40 x 15 mm and the amplitude characteristic is ±1 g. The frequency-response curve is 0-100 cps.

*Trans. Ed. Note: The second signal system is a cortical system which is related to the development of speed and thought. It consists of conditioned stimuli formed by words and their connections.

Two types of transducers were used to investigate the motor activity of animals. One of them was a potentiometer, which was controlled by a caprone string that was connected to the harness of a dog. Three of these transducers, which are attached at different points in the cabin and recorded animal movement along three mutually perpendicular axes, make it possible to obtain an idea of the spatial position of the animal and its motor responses. However, this is not sufficient for a study of the magnitude of animal efforts; therefore, B. A. Zhuravlev [117] proposed transducers of another type, which are built into the cables which secure the dog to the cabin floor. These contact potentiometer pickups were used only when a cable became taut, and they changed their resistance in proportion to the applied force.

An analysis of movements was conducted by means of comparing actograms with a television picture. Because of the combined evaluation of all data, it was possible to come up with an idea about the behavior of animals under weightless conditions [18, 117]. Telemetry recording of actograms also is of definite value for evaluating other indices since it makes it possible to determine the artifacts related to animal movements.

Many diverse methods have been proposed for investigating the motor activity of animals: recording the oscillations of the bottom of a cage made out in the form of a diaphragm and connected to electromagnetic transducers [738]; recording the number of interruptions in a beam of light passing through a chamber containing an animal [721]; attaching a magnet to an animal and recording the emf that appears in coils which are located in various points of a cage [423], and other methods [143, 675, 726].

In addition to these methods, special pickups can be employed to estimate human motor activity. The recording of differential actograms is of much interest. For instance, it was shown that even during uniform motion of the forearm its speed in different sections is unequal [272]. The importance of recording motor acts is indicated by the application of actographic methods in the study of the biomechanics of physical exercises [115], posture studies [153], research on higher nervous activity [353], and investigations during sleep [273] and work [469, 484]. One of the variations of differential actography is the method of recording the processes of written language (see below) which we developed.

Electromyography

Investigations of muscular biopotentials are of much interest for evaluating the mechanisms of motor coordination and the peculiarities of biomechanics under zero-gravity conditions.

Electromyography is one of the methods which makes it possible to investigate the process of muscle contraction under the conditions of an integral organism. An important role is played by electromyography when evaluating the state of muscular tonus [136, 283]. Ye. M. Yuganov, I. I. Kas'yan, and V. I. Yazdovskiy applied an electromyographic procedure for studying the influence of weightlessness on the state of muscular tonus in animals during flight in the cabins of ballistic rockets [282]. Electromyography has an important value in the study of work and fatigue [604, 698, 641, 225, 150, 217].

Biopotentials of muscles are characterized a very wide spectrum of frequencies and amplitudes. Thus, Volkers and Candil [711] recorded electromyogram in a range up to 130 kilocycles and noted essential distinctions in the content of the high-frequency components of muscular biopotentials in sick and healthy individuals. These authors express an assumption concerning the possible radiation of electromagnetic energy during muscular work.

It usually is considered sufficient to record electromyograms in a range from 10-30 to 300-500 cps [136, 284]. Human muscular biopotentials are recorded by means of attached, surface electrodes, and those of animals are recorded by means of implanted electrodes.

Experience in telemetry recording of electromyograms in Soviet space research was obtained during the flight of third Soviet orbital spacecraft. The "integral" electromyogram recording method was employed for transmitting relatively high-frequency signals on muscle biopotentials (to 500 cps) through telemetry channels. This method consists of detecting and integrating the output signals of the amplifier. The "envelope in this case corresponds the amplitude-frequency response of the electromyogram, i.e., at uniform frequencies it is directly proportional to amplitude, and at equal amplitudes it is proportional to frequency. Figure 86 illustrates a sample synchronous recording of a "natural" and an "integral" electromyogram of a dog while bending its head. As can be seen from the figure, on the biopotential changes caused by movements are well recorded on the integral electromyogram. Satisfactory results were also obtained in an investigation of static muscle tensions. Thus, the "integral" electromyography method makes it

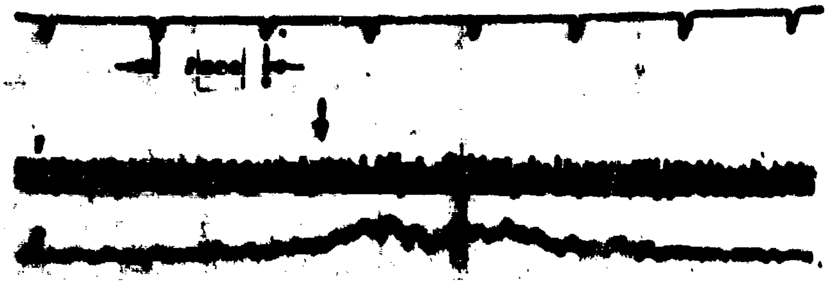

Fig. [illegible]. Electromyogram of the neck muscles of a dog while bending its head (indicated by the arrow). 1 — "natural" electromyogram; 2 — "integral" electromyogram.

possible to obtain data on electromyogram changes evcked by movements and static loads, which, in combination with an actogram, can be used for the characteristics of the motor acts of an animal in flight. The integral electromyography method also was used in certain foreign investigations [333, 427, 720]. The authors note a direct relationship between integral electromyogram readings and total muscular activity, amount of load, and functional activity (respiratory muscles) [427].

The theoretical basis of the applied method of "integral" electromyography ensues from the following positions [207]. The parameters of an electromyogram are determined by the number of motor units that are active at a given moment, the discharge frequency in each of them, and the degree of their synchronization. During isometric contraction, the area of an electromyogram is proportional to the contraction force, but this relationship is disturbed during fatigue, since the synchronization of motor units is amplified. For moderate and medium loads, the mean amplitude is a measure of the force, and the mean frequency is a measure of the load. Thus, the "integral" electromyogram during metered loads makes it possible to investigate the fatigue process, and during spontaneous activity it provides an estimate of the mean force expenditures, which is directly related to the study of metabolism.

The purpose of the first investigations in flight was to compare the level of spontaneous muscular activity under conditions of normal, increased, and decreased gravitation. Considering that the head of an animal actively participates in all motor responses (orientating, food, defensive), the electrodes were implanted in the region of the splenius cervitis. To obtain control recordings, a 2.0-2.5 kg weight was suspended to the head of a dog. There then appeared static muscle tensions, which were well recorded by the described method.

In addition, other methods of tapping muscular biopotentials were investigated.

Biopotentials of the muscle groups which bend the launch were recorded from electrodes that were located in the mid-third of the haunch. Recording was conducted both in the calm state of a dog in the standing, sitting, and prone positions, and also during the transition from one state to another and under conditions of "suspending" the dog on its stomach. As a result, rather distinct data were obtained which made it possible to estimate the degree of muscular loading. Experiments were also conducted by the "complex" electromyography method, which consists in recording the total biopotentials of a large number of muscles. This approach involves a study of the state of muscular tonus. When the area of the biopotential lead is large, the specific character of the bioelectric responses of individual muscle groups is lost. The total overall level of muscular activity is estimated.

The electromyography method is of much interest when investigating human working capacity. V. D. Moncharov reports on electromyographic investigations with the application of an electrical integrator. The integral values of muscle biopotentials were higher during physical work than under static conditions. The author explains this by the fact that the best conditions for manifestation of the influence of the central nervous system by the involvement of new muscular units are created during dynamic work [177].

Methods of automatic electromyogram processing have lately been extensively employed, which makes it possible to operationally evaluate the state of the muscular system in the process of work. Large prospects are opened up by the application of contemporary mathematical methods, e.g., auto- and cross-correlation analysis [207].

Electroencephalography

The recording of electrical activity of the brain to a certain extent makes it possible to evaluate the functional state of the cerebral cortex [114, 122, 146, 151]. Electroencephalography data are related to the most diverse sides of vital activity — from the metabolic processes on the cellular level (slow bioelectric oscillations) [13] to higher psychic functions [354, 585]. It is natural, therefore that there are many works on electroencephalography and the application of this method in the study of individuals whose profession requires an extreme degree of nervous tension. There is a great deal of literature with respect to electroencephalographic research on pilots, both for examination and selection [667], and

also for the purpose of monitoring the state of alertness [472] and stresses in flight [704, 705, 764]. Sem-Jacobson's data on the results of electroencephalography of jet pilots during bomb runs and vaious maneuvers are interesting [540]. It has been established that individuals without essential electroencephalogram changes belong to the group of pilots that have executed their mission well. Individuals with electroencephalographic changes (slow waves), as a rule, had poor flight tolerance and did not completely execute their missions.

American researchers are extensively studying the possibility of the application of electroencephalography for evaluating the stress of space flight [306]. The United States has also created miniature equipment to be placed in the astronaut's helmet [812], and has conducted a large series of electroencephalographic investigations on monkeys during the action of accelerations and vibrations [305]. Methods for recording brain biopotentials in animals are being developed [424, 430, 431, 496]. However, the first electroencephalograms from outer space were obtained by the Sov[illegible] Union [74, 86].

As it is known, there are two forms of electrical cerebral activity: spontaneous activity and evoked potentials [146]. Spontaneous (background) activity implies the general and continuous activity of the brain which is observed in the absence of special external stimuli. The evoked or reactive potentials appear against the background of spontaneous activity in response to the stimulation (direc[illegible] or ind[illegible]) of ganglion formations. In the space flights of the "Vostoks," only spontaneous electrical activity of the brain was recorded.

The main purpose of the application of electronencphalography consisted in providing for medical monitorin[illegible] the functional state of the cerebral cortex. The task of obtaining scientific materials on the influence of flight factors on brain biopotentials had a coordinative character. The recording of electroencephalograms under space flight conditions demanded the solution of several methodological problems: reliable contact of electrodes with skin for several days; selection of the most effective electroencephalographic leads from the standpoint of medical monitoring and noise immunity; distribution of electrodes in the space beneath the helmet in such a way as not to cause discomfort or difficulties during work.

Diverse variants of electroencephalographic research were tested when solving these problems. EEG recrodings were made at different points of the cranium, mono- and bipolarly, with a study of the reactions to opening and closing the

eyes and to picking up rhythm. The noise immunity of the recordings also was investigated during blinking, compressing the jaws, turning the head, and moving the arms and the trunk. The following bipolar leads were studied: "forehead-occiput," "occiput-occiput," "forehead-forehead," "forehead-sinciput," and "sinciput-occiput." The following monopolar leads were investigated: "frontal, sincipital, and occipital," on the right and on the left.

As a result of all the experiments, the "forehead-occiput" lead was selected. This lead also has been widely employed in anesthesiology [113] for monitoring the state of patients during surgical operations. Indeed, the "forehead-occiput" lead also has opponents who assert that the opposite phase directivity of points "Л" [forehead] and "З" [occiput] introduces distortions into the curve [87]. In our opinion, these dangers refer only to research electroencephalography. In an electroencephalogram recording that is made for purposes of medical monitoring, the survey lead "forehead-occiput" is the most expedient one.

Reliable sustained contact of electrodes with the skin was ensured by the application of contact pastes and depilatories. Electrodes similar to the EKG type, together with an orlon washer-lining, were mounted on the inner surface of the helmet. Wires were sewn under the lining and were drawn out into a common plug connector. The described biopotential lead system was checked out in multi-day experiments and indicated good results.

To ensure the possibility of recording electroencephalograms on the already existing electrocardiographic channels of the on-board equipment, special preamplifiers were devised. The application of preamplifiers located on the astronaut, besides the purely technical advantages, has a definite value in the sense of increasing the noise immunity of the EEG channel.

During space flight, electroencephalograms were recorded in A. G. Nikolayev, P. R. Popovich, V. F. Bykovskiy, and V. V. Tereshkova. In P. R. Popovich, for technical reasons, the recordings were of low quality, small amplitude, and vascular interferences (R wave of EKG) were present. The recordings of the remaining astronauts were sufficiently high-quality. The electroencephalograms recorded during flight reflected blinking and motor activity of the astronaut. During analysis, it is necessary to carefully select separate sections of the curve which are free from interferences. All rhythm forms are well defined in the "space" electroencephalograms: alpha (8-13 cps), beta (14-30 cps), delta (1-3 cps), and theta (4-7 cps). These types of bioelectric activity are represented in the form

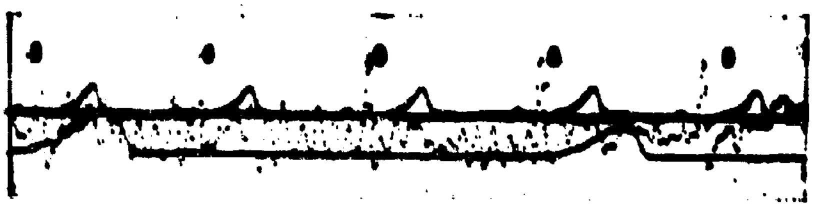

Fig. 87. Electroencephalogram of V. F. Bykovskiy during space flight.

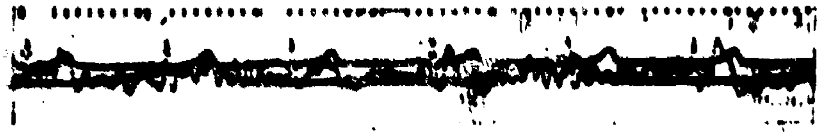

Fig. 88. Electroencephalogram in space flight (V. V. Tereshkova).

of telemetry recordings in Figs. 87 and 88.

Galvanic Skin Response

As it is known, the electrical conductivity of the skin depends on the state of the vegetative nervous system [302, 303, 304]. The degree of electrical conductivity of the skin is determined by many factors: the activity of the sweat glands, the permeability of biological membranes, the hydrophilic nature of the skin, and the blood supply. Under the influence of various factors there can occur changes in electrical conductivity. Such factors can be painful sensations, neuropsychic tension, and various afferent stimuli (light, sound). Changes in skin resistance frequently are designated as the galvanic skin response inasmuch as they are accompanied by changes in the galvanic potential of the skin (I. S. Tarkhanov's phenomenon, 1889).

There are two methods of recording galvanic skin responses: Tarkhanov's method (recording the electrical potentials of the skin) and Ferrier's method (recording the electrical resistance of the skin). Both methods give identical results. Galvanic skin responses are the result of a change in the current balance of the sympathetic and parasympathetic systems. These responses are non-specific to a higher degree inasmuch as they can be related both to complicated neuro-endocrine shifts and also to changes in the information flows in the central nervous system. Undoubtedly, an important role in the realization of galvanic skin responses is played by reticular formation.

Upon stimulating the sympathetic system, the galvanic skin response appears

in the form of a drop in electrical resistance (the result of intensive activity of the sweat glands) or in the form of increased electronegativity (the result of neuro-energetic processes which are accompanied by a change in the electrical charges on the surface of the skin). Parasympathetic responses are accompanied by inverse measurements.

There are spontaneous and evoked galvanic skin responses. Significant spontaneous responses frequently are observed in mental instability, e.g., in schizophrenics [537]. During flights on a Keplerian parabola, oscillations in electrical resistance were detected [699], which apparently cannot be said to be spontaneous inasmuch as they are related to the intermittant action of weightlessness and G-loads. The galvanic skin response to some stimulus is characterized by its latent period and amplitude. In schizophrenics, an essential lengthening of the latent period is noted. In general, the duration of the latent period is inversely proportional to the depth of cortical inhibition [221].

Slow (hourly, daily) changes in skin resistance also have a definite diagnostic value. It is known that there is observed an increase in electrical resistance of the skin during sleep. This makes it possible to monitor the state of sleep and consciousness [600]. When the vestibular apparatus is stimulated, a decrease in skin resistance is observed [561].

Galvanic skin responses are considered as an index of the alertness and consciousness of a pilot. Various emotions — excitement, fear, apprehension — are clearly recorded by this method; therefore, it is recommended in many telemetry programs for space research [415, 512, 413, 756]. This method is being used successfully for monitoring and research in aviation [73, 699].

Thus, galvanic skin phenomena can be used to evaluate the state of the vegetative nervous system and to indirectly assess the functional interrelationships in the cerebal cortex. This determined the application of the method of measuring electrical skin resistance leather under space flight conditions.

Two types of instruments were developed for recording galvanic skin responses (see Chapter 3): one for measuring the absolute values of skin resistance and its slow changes; the other for recording only fast oscillations of resistance. The "Vostok-3" and "Vostok-4" spacecraft had an instrument of the first type, while the "Vostok-5" and "Vostok-6" had an instrument of the second type. The problem of the electrodes was very complicated. It was necessary to ensure prolonged recording of electrical skin resistance, whereas it is known that even in brief

investigations errors are observed which are caused by the increase of inter-electrode resistance due to a disturbance of contact and polarization phenomena [341, 389]. In addition, it was important to ensure the absence of uncomfortable sensations as a result of the prolonged location of electrodes on the skin. O'Connell and his associates investigated five types of electrodes for recording galvanic skin responses and found that the best electrodes were those of the Ag-Cl-sponge type. However, these investigations considered the recording of galvanic skin responses for one hour. Under the conditions of space flight, it was required to ensure recording for several days. The use of electrodes of this type, just as for electrocardiography, good skin treatment, and proper selection of an appropriate paste make it possible to successfully solve this problem (I. T. Akulinichev, A. Ye. Baykov). The electrodes were placed on the plantar and dorsal surfaces of the astronaut's foot and were secured with the aid of an elastic bandage. Figure 89 illustrates recordings that were obtained during the flight of A. G. Nikolayev. As can be seen, there is a daily dynamic character of the magnitude of skin resistance: it decreases towards evening and increases by morning. In propelled flight and before descent, due to emotional tension, a lowering in electrical resistance of the skin was observed.

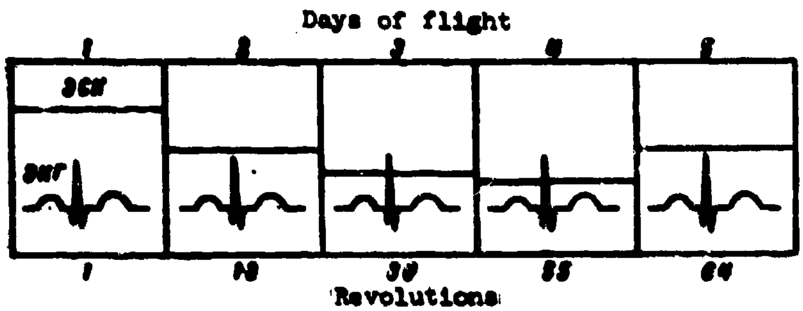

Fig. 89. Schematic copy of recordings of electrical skin resistance [ESR] (ЭСК) of A. G. Nikolayev in space flight.

In astronauts V. F. Bykovskiy and V. V. Tereshkova, rapid oscillations of electrical skin resistance were studied. This essentially amounted to recording spontaneous responses. The response level was monitored during the influence of space flight factors. On the recorded curves it was possible to distinguish three types of responses: 1) slow single-phase, 2) fast two-phase (duration less than 2 seconds), and 3) combined responses.

As a result of the investigations it was established that the average reactance

of the astronauts (expressed as the average reaction per minute) varies from 6-8 to 2-3. Reactance was increased in the beginning and at the end of the flight, which is caused by higher neuropsychic tension. In separate moments of flight, in connection with emotional tension, a very high reactance is observed (up to 15 reactions per minute): e.g., directly before launching, and also prior to descent. At the time of severe emotional stress before V. V. Tereshkova's descent, along with an expressed galvanic skin response, a change in the seismocardiographic curve was recorded in the form of a third oscillatory cycle. The presence of the extra cycle indicates the appearance of additional forces (accelerations) in the beginning of the diastolic period. It is most likely that these forces are related to the accelerated filling of the heart. A similar picture can be observed during the intense flow of blood to the ventricles, i.e., when blood is deposited in the pulmonary vascular channel and the venous system [511]. Emotional stress causes a sympathetic-tonic vascular reaction of the hypertension type. As shown by V. V. Parin and V. Z. Meyerson, in an acute case of reflex hypertension in the greater circulatory system, blood is displaced into the lesser circulatory system, and the volume of blood in the lungs and the pressure in the pulmonary vessels is sharply increased [203]. Conditions are then created for accelerated filling of the left ventricle, and consequently, for the appearance of a third, additional, seismocardiogram cycle. A similar situation, however, is brief and transient. Thus, the presence of a third seismocardiogram cycle was observed in flight for only about 15 sec. The fact is that an increase of pressure in the pulmonary vessels leads to the appearance of an unloading reflex reaction (V. V. Parin's reflex) which consists of a drop of blood pressure in the arteries of the greater circulatory system, and the appearance of bradycardia and blood deposition in the spleen [1189]. This reaction is one of the parasympathetic reactions [409]. Very interesting recordings were obtained at the time of awakening (Fig. 90). Here we have an example of an "evoked" galvanic skin response. The recording clearly illustrates how shutting the eyes occurs at the height of inhalation (electro-oculogram). A little earlier, the slow rhythm of cerebral biopotentials is replaced by alpha- and beta-waves. A drop in skin resistance (rise of curve) coincides with opening the eyes.

The nonspecific character of galvantic skin responses dictates the necessity of their constant comparison with other physiological indices, with radio-conversation recordings, and with television pictures. At present it is difficult

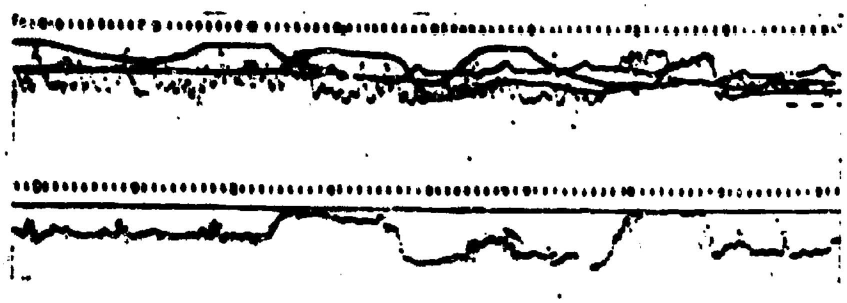

Fig. 90. Changes in physiological parameters at the time of awakening under space flight conditions (V. V. Nikolayeva-Tereshkova). Top — pneumogram, electrocardiogram, galvanic skin response, electroencephalogram: Bottom — seismocardiogram recorded jointly with electrooculogram.

to estimate the value of this method for purposes of medical monitoring; here it is necessary to gain further experience in the recording of spontaneous and evoked reactions under the conditions of various tense situations.

The methods of complex evaluation of galvanic skin responses with known stimuli can be importance: e.g., with stimulation of the vestibular apparatus, "psychologic tests," and in the study of working capacity. American researchers are working on the creation of automatic analyzers of galvanic skin responses [32].

Problems of Evaluating Work Capacity Under Space Flight Conditions

Flight experiments with animals showed that weightless conditions do not cause shifts in the neuromuscular system which would prevent the normal vital activity of the animals. The animals ate, attended to their natural needs, and reacted to various external influences (e.g., turning on light in the capsule). Investigations on laboratory rats, which were conducted before and after flight, indicated the preservation of earlier developed conditioned reflexes [18, 86]. According to actography data, which was supplemented by television materials, it was possible to make a conclusion concerning the fact that the motor responses of animals under weightless conditions remain sufficiently fast and adequate. Electromyographic investigations did not indicate an essential changes in muscular tonus. Thus, even the preparation of the first manned space flight did not encounter any gross changes on the part of the neuromuscular system. American researchers, however, detected certain disturbances in the work capacity of an chimpanzee in powered phase and the descent phase during ballistic and orbital flights under Project "Mercury" [483, 676]. Nonetheless, the investigation of

human work capacity and, in particular, the state of the human neuromuscular apparatus was of much interest. Investigations of human work capacity and fatigue differ in principle from the study of the problem of fatigue in the general biological program on animals and other biological specimens. One of the most important methodological premises in the study of human work capacity and fatigue consists in the fact that it is necessary to conduct the investigations under conditions which are as close as possible to the natural conditions of human activity [217].

The central-cartical theory of fatigue is presently considered to be the most proven one. This theory is based on the works of I. M. Sechenov, I. P. Pavlov, and N. Ye. Vvedenskiy. The central-cortical theory is considered in the monograph "The Problem of Fatigue" by V. V. Rozenblat. The problems of work capacity and fatigue are the subject of many publications [84, 102, 217, 457, 509, 575, 625, 775]. This problem is considered to be one of the most important and urgent problems of physiological science. Prime attention was previously allotted to the study of muscular work; now, the automation of control processes and the increase of man's role in complicated systems have led to the necessity of paying special attention to mental work capacity. However, both mental and physical work capacity, in spite of the distinction in methods of evaluation, have a common cortical mechanism of fatigue and influence one another [217].

Work capacity can be estimated both according to the character of performance of the work itself, and also on the basis of changes in the state of the various organs and systems as a result of performing a given task. According to V. V. Rozenblat [217], changes in work capacity can be expressed in the following forms: a) a decrease in the quality of work, b) a decrease in the quantity of the work, and c) a disturbance in coordination of the processes involved with the performance of a given task.

The varied activities of an astronaut under space flight conditions provides a great deal of material for evaluating his work capacity. The introduction of radio communications, flight-log recording, special observations, and actions in orientating the spacecraft — all this professional activity of an astronaut characterizes his work capacity. But the fulfillment of all elements of the flight missions makes it possible to discuss only one side of work efficiency, the absence of its qualitative changes. To explain quantitative shifts and especially changes in coordination of working processes, it is necessary to introduce definite,

well-measured actions into the flight program.

The method of programmed medical research which we developed to include the active participation of the astronaut is one of variations of a measured working load. Here, first of all, time measurement is accomplished. A strict time schedule and trained motor skills create as if a "chain reaction" which consists of motor acts that are strictly measured in macrointervals of time. According to A. A. Ukhtomskiy, the macrointerval is an important index of the lability of system formations. N. S. Tochilov developed the theoreticalfundamentals for the analysis of integral motor acts with repeated activity of various complexity [250]. He considers the time and content of the motor acts: its active (movements) and passive (pauses) elements. Element-by-element analysis of time-study data makes it possible to evaluate the lability of the motor analyzer with respect to the generla conditon of the organism. In a programmed investigation, the analysis of a set of recordings not only makes it possible to clarify the active and passive elements, but also to analyse the content of the work performed and to evaluate its quality. It should be noted that special instruments have been constructed abroad for the simple investigation of only "pause-work" cycles: e.g., a device for recording the moment contact with the control stick [713].

Considerable attention is presently being given to the disturbance of the information processes related to the performance of a specific task. The benefit of the cybernetic concept of "man-machine" also has appeared in stidies on the problem of work capacity and fatigue. V. S. Farfel' and his associates investigated changes in work capacity on the basis of indices of the volume of perceived information. They studied the tasks of subway operators and took the number of visual signals appearing along the route in 30 minutes as a criterion. It was established that toward the end of the work shift the volume of perceived information decreases [258]. The information processing in the brain [624] and the reactions of an operator to various stimuli [432, 520] are being studied to evaluate human work capacity. If we consider programmed research from the positions of the "man-machine" concept, it is possible to imagine the activity of an astronaut as a process of consecutive realizations of a standard set of "models of the necessary future" which are preliminarily coded in his brain, and to consider his action as a control process. As a result of comparing (automatic or manual) the information obtained on the activity of an astronaut with the assigned program, it is possible to estimate the quality of the control process. Thus, programmed

research makes it possible to evaluate astronaut work capacity quantitatively on the basis of the size and number of errors made during fulfillment of the program.

Finally, the possibility of evaluating the coordination of working processes according to programmed research data was brought about by the fact that in the process of performing an assigned sequence of actions several vegetative and neuromuscular indices are recorded which reflect the state of the organism at the time of the activity. The mutual relationships between indices and their changes as compared to the standards obtained during training sessions permit a detailed evaluation of many interdependent processes which ensure the realization of specific motor acts.

Evaluating work capacity on the basis of reactions on the part of the circulatory, heat-regulation, respiratory, and other systems is one of the widely used methods. The concept of the reflex interaction of various system has long been recognized in the physiology of work. Respiratory oscillations of muscular tonus were described by Yu. S. Yusevich [284]; M. R. Mogendovich and his associates have been working out the problems of the relation of locomotion to the state of visceral systems for many years [45]. The simultaneous recording of motor and vegetative functions occupies a conspicuous position in diagnosing fatigue [1, 120, 217, 239, 436, 439, 641, 813]. Data have been published concerning the influence of fatigue on the daily period of physiological functions [166, 219, 342]. Investigations of vegetative indices for manifestation of emotional stresses are well known [213, 320, 344, 410].

We must not forget to mention the group of methods involved with the study of the reactions of the nervous system of a subject ot various stimuli: e.g., acoustical [72], visual [303], and electrical [26, 149].

The problems of studying human work capacity under the conditions of actual or simulated space flight are the subject of a large number of investigations. These investigations concern the vegetative and emotional sphere of the astronaut, his mental and physical work capacity, the possibility of spacecraft control, and the fulfillment of a program of scientific investigations. The first "Vostok" flights proved the possibility of maintaining the necessary level of human work capacity under space flight conditions [293, 294, 295]. Starting with the "Vostok-3," new methods of monitoring and research, electroencephalography and recording of galvanic skin responses were introduced. During the flights of the "Vostok" spacecraft, astronaut work capacity was estimated according to the volume and

quality of fulfilling the flight mission in various phases of flight, and also according to the performance of a large number of tests to study the neuropsychic sphere, which were directed towards the manifestation of mental fatigue. These tests include: a proofreading test (the astronaut had to loudly call out geometric figures that were drawn on a table: e.g., a rhomboid, triangle, square, and others); the reading regime was determined by an instruction (horizontal reading, across one figure, vertical reading, across two figures, and others); a numerical test: mental arithmetic; determination of "sense of time" (preservation of the ability to count off a specific time interval without a stop watch). These investigations showed that under conditions of prolonged weightlessness a man can perform various, quite complicated tasks. Investigations under laboratory conditions, where the various aspects of space flight were simulated — prolonged isolation [93, 125, 499, 577], control processes [50, 567, 602], various activity [625, 803] — made it possible to reveal a large number of interesting facts not only with respect to work capacity, but also with respect to the state of the vegetative functions. Thus, a close relationship between the research methods employed for evaluating the neuromuscular and vegetative functions of an organism is noted.

We attempted to develop a specialized program for investigating work capacity on the basis of studying various reactions and loads. We took three circumstances into account.

1. In the process of executing the program, the organism of the test subject should be consecutively on different functional levels: complete rest, ordinary activity, tense mental activity, and tense muscular activity.

2. Three types of reactions must be recorded: indirect, by way of the 2nd signal system; evoked by the 1st signal system; vegetative (unconditioned) reactions.

3. Physiological functions which characterize the state of the cerebral cortex, the muscular system, respiration, and blood circulation must be recorded.

After selecting a task envolving a light tableau as the mental load by means of the conditioned-motor method, and work on a dynamometer as the muscular load, we encountered difficulties in selecting an activity which would be "ordinary." Finally, we decided on a writing test which, under flight conditions, consisted in the task of keeping a diary and, apparently, did not cause increased tension in the astronauts. The processes of written language are among the daily actions of almost anyone and are essentially well automated motor skills. The investigation of the processes of written language is presently of interest not only to

specialists in forensic medicine [168] and psychiatry [164], but also to engineers working in the field of the problems of identifying images [502].

We will latter describe two new methods - dynamography and graphometry (the recording of written language) - which were developed specially for purposes of programmed research under space flight conditions, and we shall then give an account of a specialized program and its test results.

An electrodynamograph was developed at our suggestion for recroding dynamograms (V. R. Freydel' and associates). Its scale was linear in a range of up to 50 kilograms; the use of a potentiometer provided a frequency range from zero. Strength, endurance, and fatigue can be studied with the aid of an electrodynamometer. Strength measurement is an extremely simple procedure and does not provide sufficient information for evaluating work capacity. Endurance is usually studied on the basis of the time of sustaining a force that is equal to half of the maximum [67, 217] or with respect to the amplitudes of strength in the beginning and at the end of a given time interval, during which a force close to maimum is sustained [71].

The study of fatigue was conducted by the ergography method. The test subject was assigned a compression rate and force (or these parameters were arbitrary) and work capacity was then considered within the limits of a specified time interval. With the aid of the dynamograph, it was possible to record responses during the investigation of conditioned motor reactions. Together with the dynamogram, an electromyogram of the forearm flex or longus. Silver electrodes were attached with paste by means of elastic cuffs in the upper and lower third of the forearm (Fig. 91). As it is known, during muscular fatigue there occurs an increase in the amplitude and a decrease in the frequency of the biopotentials [566, 698, 604, 747]. The recording of a dynamogram together with an electromyogram is known as ergoelectromyography. This method makes it possible to quickly determine the approach of fatigue on the basis of the opposite directivity of changes in recordings: in the dynamogram it is a decrease in amplitude, and in the electromyogram it is an increase in amplitude [628].

A new method for investigating written language is based on recording the movements of the writing implement (pencil). In distinction from N. M. Rachkov's method, which is described by A. I. Mantsvetova and V. F. Orlova [168], in our method the forces applied to the pencil point during writing are not recorded; the speed and direction of its movement at each given moment of time are

Fig. 91. Recording (a) a dynamogram and an electrogram (b) — photograph of electrode with retainer.

recorded [200].

The instrument consists of two wooden (or plastic) platforms that are rigidly connected by means of four flat spring elements made from organic glass (Fig. 92). The mutual translocation of platforms is possible only in a direction perpendicular to a spring plane. Inside the instrument there are a permanant magnet and induction coils which are attached to the opposite platforms in such a way that the induction current at the coil output is maximum during their mutual translocation (together with the platforms). To remove the various interferences of a mechanical and electrical character, a capacitance on the order of 5-10 mf is connected in parallel to the coil. If a sheet of paper is placed on the upper platform of the instrument and some letter or number is written on it, the movements of the pencil will be transmitted to the platform and cause it to move. Due to this, in the coil there will appear an induction current that is proportional

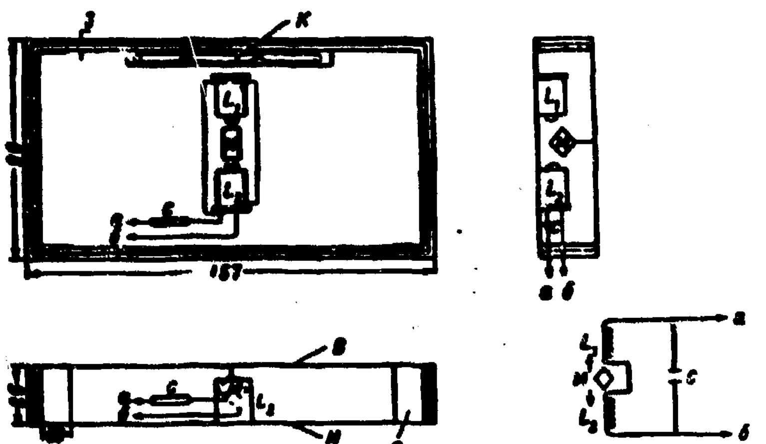

Fig. 92. Instrument for investigations of written language. B — upper platform; H — lower platform; M — magnet; L — inductance coil; K — device for securing paper; П — springs (organic glass); C — capacitor; a, б — outputs to recording instrument.

to the speed of motion of the pencil and the sine of the angle formed by the direction of displacement of the platform and the direction of motion of the pencil. A maximum signal at the instrument's output is obtained when these directions coincide. Maximum output voltage does not exceed 0.5-1 mv and the signals were recorded by means of conventional EKG channel. To facilitate work with the instrument, the paper is precut to the size of the upper platform and secured by a clamp from the folder.

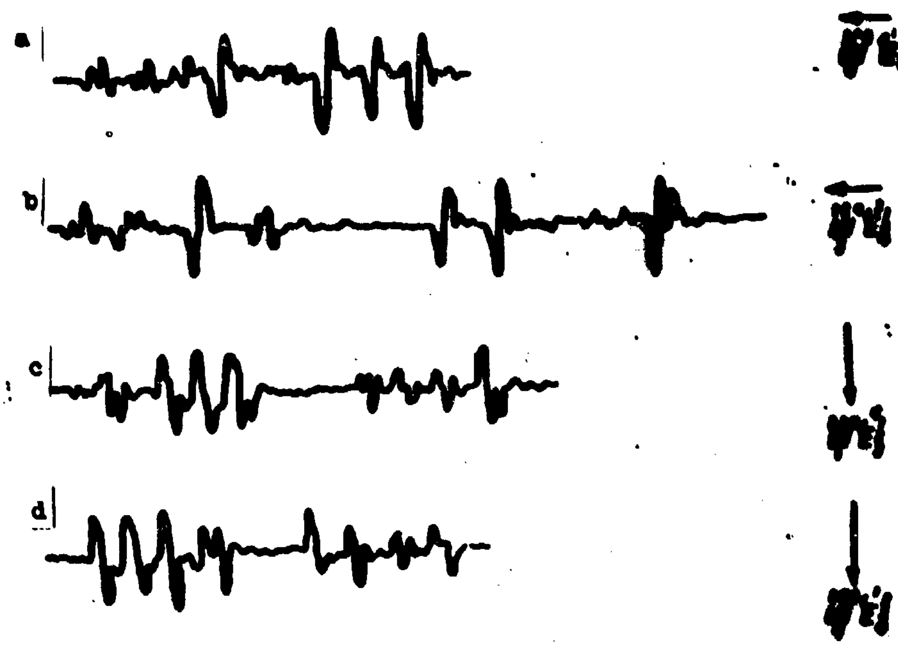

Fig. 93. Oscillograms of the letters Ш and Е which were obtained during horizontal (a and b) and vertical (c and d) movement of upper platform.

Figure 93 illustrates oscillogram of the letters Ш and Е which were obtained with the aid of the described instrument. The inscriptions of these letters are very similar and they consist of an identical number of elements. If the letter Ш is turned at 90° clockwise, the letter Е will be obtained. The oscillograms of the letters Ш and Е which were written horizontally are analogous to the oscillograms of the letters Е and Ш which were written vertically. This is related to the fact that the elements which coincide in direction with the direction of platform translocation of the instrument have the greatest amplitude. The sequence of writing the elements of the indicated letters is determined very well on the oscillograms. Figure 94 illustrates on oscillogram of the number 6 and the methods of analyzing it. As can be seen, a very precise time and amplitude

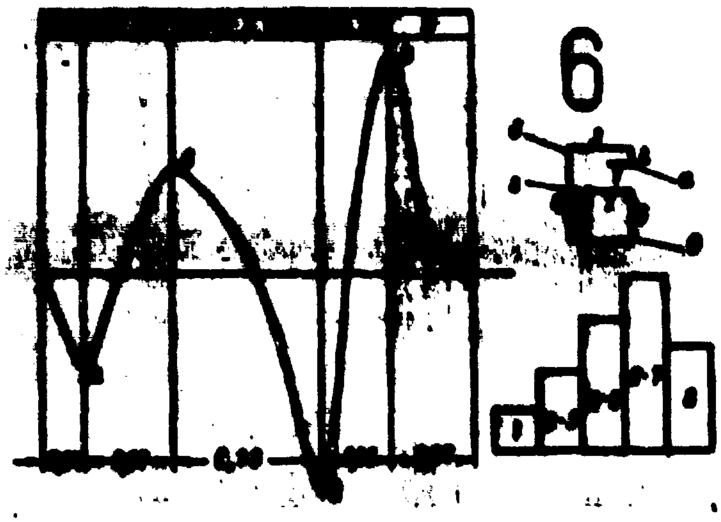

Fig. 94. Oscillogram of the number "6." Characteristic points and segments of the graphic depiction of the number "6" are shown on the diagram at left center. At bottom right under the oscillogram is a time graph of motions, and on the left is a diagram of the speed of the motions.

analysis of written language is possible.

A consideration of the examples given above shows that the new method makes it possible to objectively analyze the motor act that is performed in the process of written language from the point of view of its following indices:

a) the duration of the entire motor act and its separate elements;

b) the speed of separate motions;

c) the direction of motion when executing each element;

d) the sequence of elements of the motor act.

It is natural that the above-described simple version of the instrument does not make it possible to reveal all the possibilities of the method. In particular, in our opinion, an important role could be played by the vector principle of analysis in which all three motion components would be recorded. It is quite probable that the shape and area of certain loops, and also the direction of motion of the vectors of each element, will considerably expand the information on the motor acts of written language.

A specialized program was developed for investigating work capacity. The total time of investigation is 7 minutes. The program anticipates three standard writing tests: the background, after mental exercise, and after physical exercise. Some of the research methods are electrocardiography, seismocardiography,

pnemography, and arterial oscillography. The indicated program was tested during a 20-day experiment under conditions of isolation and limited mobility. Programming of work-capacity investigations made it possible to detect a number of changes at the end of the experiment which indicate the absence of fatigue phenomena. The analysis of vegetative reactions and, in particular, the rhythm of heart contractions is of much interest. Table 24 shows the dynamics of RR interval of an electrocardiogram in the process of executing a specialized programmed investigation. The data obtained from one of the test subjects in the beginning and at the end of the experiment are given. An analysis of the table information gives us a basis to consider that toward the end of the experiment there is a certain increase in tonus of the parasympathetic nervous system. Investigations were conducted during the flight of the "Voskhod" on a combined program which was formulated on the basis of several specialized programs (D. G. Maksimov). The program consisted of several parts (four).

1. Investigation of the central nervous system, i.e., recording an electroencephalogram with eyes open and closed.

2. Investigation of muscular work capacity, i.e., recording a dynamogram (60 compressions of hand dynamograph at a rate of one per second).

3. Investigation of precise motor coordinations by means of recording the motions of the writing implement in the process of writing (with eyes open and closed).

4. Investigations of the functional state of the vestibular apparatus, i.e., recording an electrooculogram during the performance of vestibular tests (stimulation of vestibular apparatus).

Table 24. Some Static Indices of a Dynamic Number of RR Intervals of an Electrocardiogram During the Execution of a Specialized Program of Medical Research Under the Conditions of a Prolonged Experiment

Activity of tester	2nd day of experiment				15th day of experiment			
	M, sec	σ, sec	V, %	ΔX, sec	M, sec	σ, sec	V, %	ΔX, sec
Sits calmly, without tension	0.74	0.066	8.9	0.25	0.82	0.108	12.5	0.4
Writes (1)	0.74	0.074	10.0	0.35	0.77	0.094	12.5	0.5
Responds to conditioned signals	0.66	0.055	8.3	0.20	0.72	0.074	10.2	0.35
Writes (2)	0.75	0.082	10.9	0.4	0.77	0.085	11.0	0.35
Dynamography	0.07	0.072	10.7	0.3	0.74	0.059	7.9	0.3
Writes (3)	0.75	0.068	9.0	0.35	0.75	0.067	8.9	0.3

The time of execution of the entire program on the whole was calculated in such a way so as to perform consecutive recording of all the indicated parameters. The programmed research was conducted by the physician on himself and on the other members of the crew in the beginning, middle, and at the end of the flight. Some unique scientific data were obtained.

CHAPTER 10

METHODS FOR STUDYING THE VESTIBULAR APPARATUS

After vestibular-vegetative and vestibular-sensory disorders were detected in G. S. Titov's flight [294], the physiological measurements began to include parameters which make it possible to characterize the functional state of the vestibular apparatus. The vestibular apparatus is closely related to numerous analyzers (kinesthetic, optic, auditory) and, together with them, performs the task of spatial orientation. V. F. Undrits [303] considers the following ways of investigating the vestibular apparatus:

1) a study of the sensitivity to adequate (accelerations) and inadequate (temperature, electricity) stimulations;

2) an investigation of the state of the vestibular analyzer during a known working load (e.g., during rotation);

3) an evaluation of the reflex reactions that accompany stimulation of the vestibular apparatus.

Investigations under space flight conditions used all of these methods. A set of four special tests was developed which alternate coordination and loading tests [295]. These tests consisted in evaluating spatial orientation with eyes closed and open, performing a series of inclinations of the head and trunk, and finger-nose tests, a determination of the possibility of performing precise coordinated actions (writing, drawing, with visual control and without it).

In estimating the various reflex shifts caused by vestibular stimulations, of much value was the complex evaluation of all the remaining recorded parameters: electrocardiogram, respiration, electroencephalogram. Starting with A. G. Nikolayev's flight, the telemetry program included electrooculography.

One of the constant reflex reactions on the part of the striated muscles in response to stimulation of the ampullar portion of the vestibular analyzer is nystagmus. There are many methods for studying nystagmus [368, 305, 552, 654, 263, 264].

The electrooculography method has been employed extensively for the purpose [569, 383, 708, 546, 637, 310, 709]; it also makes it possible to record nystagmoid movements. Electrooculography uses the recording of changes in potential difference that appear during eyeball movement. It is known that the anterior pole of the eyeball is electrically positive with respect to the posterior pole. If nonpolaring electrodes are applied in the region of the external and internal canthi, it is possible to record the change in potential difference during eye movement to the right or to the left. By placing electrodes near the upper and lower edge of the eye orbit, it is possible to record vertical translocations of the eyeball.

The performance of electrooculagraphy under conditions of a multiday space flight entails many methodological difficulties.

Thus, it is practically impossible to employ nonpolarizing electrodes. It is impossible to ensure reliable contact of electrodes with the skin for a prolonged length of time when the electrodes are located in the above-mentioned points. Therefore it was required to modernize the method and to develop a procedure for recording electrooculograms under specific conditions.

Electrooculograms were recorded in the first two flights with the use of silver electrodes that were built into spring-type plastic inserts and securely connected to the helmet. The electrodes were pressed tightly to the skin in the region of the checkbone near the external canthi of both eyes. Eye movements to the right and to the left caused both the appearance of biopotentials related to eyeball movement and also action potentials of the facial and oculomotor muscles. The magnitude of the potentials was 50-100 microvolts. This demanded the application of a preamplifier with an amplification factor of about 20. Alternating current amplifiers were used; therefore, the electrooculogram was recorded as the first derivative, i.e., a speed curve [494, 709].

Electrooculograms recorded with the aid of the indicated method have several components: those which reflect eye movement, blinking, and activity of the facial muscles. Nystagmus has a well-defined typical form on an electrooculogram.

A method of electrooculogram recording by means of detachable electrodes

located in direct proximity to the external canthi and connected to amplifiers with the aid of pushbutton plug connectors with outputs on the helmet was subsequently developed (D. G. Maksimov). This method provides more qualitative recordings, but requires preliminary instruction and training of astronauts.

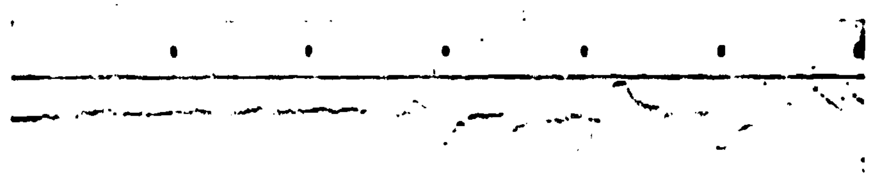

Fig. 95. Sample of electrooculogram recording during V. F. Bykovskiy's flight.

The electrooculography method was applied in four flights, whereby in the last two (on the "Vostok-5" and "Vostok-6") electrooculogram and seismocardiogram recording was applied. Simultaneous recording of two parameters with different frequency responses on one channel turned out to be very effective. There were no difficulties in analyzing the telemetry information. The amplitude of the seismocardiogram in the beginning of the flight was very low in view of the shunting of the seismotransducer by a low interelectrode resistance. As a result of the electrodes drying, there occurs a gradual increase in interelectrode resistance and the amplitude of the seismocardiogram is increased with a certain decrease in amplitude of the electrooculogram.

According to electrooculography data, it is possible to evaluate the following: oculomotor reactions; oculomotor activity: speech reactions of the astronaut; checking for the presence of nystagmoid reactions.

Various types of the electrooculographic curve were detected in flight. Figure 95 illustrates samples of recordings of single and group movements, muscular stresses, and nystagmoid movements. Oculomotor activity, which can be evaluated according to the number of eye movements, is of interest. Thus, in the beginning of V. F. Bykovskiy's flight there were observed from 100 to 180 eye movements per minute; toward the end of the flight, they amounted to 18-30 per minute. Vestibular tests also are expressed very well on an [EOG] (ЭОГ).

The "Vostok" flights demonstrated the individual character of vestibular reactions during the prolonged action of weightlessness. The manifestations of the vestibular reactions were also different. In G. S. Titov there predominated vestibular-sensory changes, although on the part of the vegetative functions there

were observed definite changes, such as expressed pulse fluctuation, lengthening of the electromechanical delay in the cardiac cycle, and others. In P. R. Popovich there were observed only illusions of position in the first minutes of weightlessness. In V. V. Tereshkova, who had no subjective complaints, several neurosomatic and vegetative shifts were noted. At present, the concept of the relative predominance of pulsation from the vestibular analyser with a lowering in activity of other afferent systems, in particular a decrease in pulsation from the proprioceptors [86], is being advanced as the main hypothesis of the appearance of vestibular-vegative disorders in weightlessness. As a result of an increase in activity of the vestibular centers, there can appear various reflex reactions. However, there are also other opinions [180]. Thus, the appearance of functional shifts can be related to relative hypoxia of the brain as a result of a possible decrease in cardiac work. A definite role is apparently played by the interrelationships between the cortex and subcortex, the type of higher nervous activity, the excitability of subcortical centers, and other factors. The data that have been obtained to the present time do not make it possible to express a final conclusion on the mechanisms of vestibular-vegetative shifts under weightless conditions. Further investigations in this direction are necessary.

Electrooculography is undoubtedly an important method for determining nystagmus, symmetry of eyeball movements when performing vestibular tests, and general oculomotor activity. The further improvement of this method should proceed in two directions: improvement of the methods of leading off biopotentials and development of appropriate functional tests. The simultaneous recording of horizontal and vertical eyeball movements and vector electrooculograms are of interest.

To investigate the sensitivity of the vestibular apparatus, in addition to adequate stimulations (head movements), inadequate electrical stimulations are proposed [281]. As it is known, electrical stimulation of the vestibular apparatus was used as a diagnostic test by physician-astronaut B. B. Yegorov during the investigations conducted on the "Voskhod" spacecraft.

In investigations of the vestibular apparatus, besides eyeball movements, trunk movements [754] and head movements are considered. For objective recording of these movements, special pickups located in the astronaut's helmet [534] can be used. The above-described seismocardiographic pickup, which is attached to the head, also can be used for these purposes.

It is expedient to device multicomponent seismotransducers with separate sensors for each mutually perpendicular direction.

Investigations of head movements are important both for the characteristics of the accuracy in performing vestibular tests, and also for evaluating the reflex reactions in response to stimulation of the vestibular analyzer. It is necessary to improve the methods for evaluating other reflex reactions also: e.g., somatic and vegetative. As it is known, one of the manifestations of vestibular-somatic disorders is a disturbance of motion coordinations. During the "Vostok" flights, special tests were conducted to evaluate motion coordination [294], which included writing tests that consisted in tracing various geometric figures with the eyes open and closed. An important role in evaluating the state of the vestibular apparatus is played by the analysis of the various vegetative reactions, pulse, and body temperature [160, 161, 182]. There are investigations which indicate the influence of vestibular stimulations on the electrical potentials of the stomach [265].

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CHAPTER 11

FUTURE TRENDS IN THE DEVELOPMENT OF PHYSIOLOGICAL RESEARCH IN ASTRONAUTICS

The great achievements of space biology and medicine in the solution of problems related to flight experiments with animals and the "Vostok" flights to a considerable extent were due to the application of physiological methods for in-flight monitoring and research. The first steps of space physiology involved the necessity of studying basically the most important systems of an organism from the point of view of general vital activity and work capacity: the circulatory and respiratory apparatus, the neuromuscular system, and the vestibular analyzer. However, for an exhaustive study of the physiology of animals and humans in space flight, the functional state and other systems and organs, and also the physiological mechanisms which unite and regulate their work, should be analyzed and evaluated [532].

Just as there exist physiological constants of a healthy individual for terrestrial conditions [653], similar constants must be created for life-support conditions in outer space. Without a clear concept of the specific character of the norm and pathology in space flight, it is neither possible to realize reliable medical monitoring of an astronaut nor to automate this process. Finally, this is related to the development of measures that must be taken to ensure normal functioning of the organism in conditions that are unusual for it and optimization of man's relationship to the spaceship systems. The expansion of our knowledge in the field of space physiology will undoubtedly proceed towards the creation of various models on Earth, but the basic means of obtaining new information on the influence of space factors on a living organism will remain the flight experiment.

One of the most important tasks of space physiology consists of creating a foundation for constructing a "space" disease clinic. Without taking into account the possible disease rate of interplanetary crews, it is impossible to plan long-term and long-range flights. Without a knowledge of the physiological regularities of the processes of vital activity under space flight conditions and during the action of various factors, it is impossible to imagine the probable disease rate in flight. In recent years, research work in the area of the clinical aspects of astronautics has been considerably intensified. Thus, Berry [327] considers in detail the problems of the application of drugs in prolonged space flight. P. V. Vasil'yev and V. Ye. Belay have investigated the influence of various pharmacologic means [63]. Waggoner [765] investigated the possible disturbances of the state of health under space flight conditions. A comparative appraisal of the psychological characteristics of astronauts and Antarctic scientists is of interest [725]. There have been works which consider, for instance, the possible changes on the part of the blood system or the procedure for investigating immuno-biological problems in space [460, 461, 280, 522]. A survey of data on the problem of expanding the range of physiological investigations in space flight will be given later.

Metabolism and Energy Exchange. Thermoregulation

The considerable physical and emotional loads in space flight, and also the rearrangement of a number of functions caused by new physical conditions (weightlessness), should also cause definite changes in metabolism and energy exchange. It is known that energy exchange depends on the cycles of sleep, rest, and work [407, 766], and also on emotional stresses [626]. Investigations of this problem are extremely important for the solution of a number of practical problems of astronautics: selection of the design and operating conditions of air-conditioning and heat-regulation systems, substantiation of requirements with regard to feeding astronauts, and the development of a rational program of work and rest in flight.

The first attempts of investigating energy exchange and thermoregulation in space flight were made during the first flight experiments with animals. Ye. Ya. Shepelev proposed a simulator instrument that made it possible to study the thermal balance of an animal and its environment. He investigated the skin temperature of animals.

Animals thermometry was conducted with the aid of flat thermistor pickups that were built into a rubber casing. The pickups were placed in the region of the back and front extremities. The pickups were connected to a potentiometer circuit with a vacuum-tube dc amplifier with the aid of a commutator once every 20 sec. Reading was performed according to the recording level and a calibration curve. The temperature standards of animals were preliminarily studied in the two indicated points. The average temperature in these regions was equal to 36 and 37.5°C, respectively. In the course of flight, cabin temperature and humidity were measured simultaneously, which made it possible to obtain an idea of the character of thermoregulation under weightless conditions.

Investigations of the energy exchange in humans can use the data obtained during the investigation of perspiration [517] and monitoring of the temperature of space below the pressure suit, the temperature and gas composition of cabin air, and the operating conditions of the air-conditioning system. However, this is all indirect data. Direct investigations of energy exchange can be based on a study of gaseous interchange. Ford and Helerstein [434] present a formula for determining energy expenditure in kilocalories per minute (ЭЭ) depending upon pulmonary ventilation in liters per minute (ЛВ):

$$ЭЭ = -0{,}52 + 0{,}173\ ЛВ.$$

There are data on the possibility of determining energy exchange according to the amount of oxygen consumed by the organism per unit time, and according to average body temperature, which is porportional to basal metabolism. Investigations of metabolism and energy exchange can be carried out on the basis of the "food ration" method (exact calculation of caloricity of food taken) with monitoring of body weight. Finally, it is quite possible to employ the method of direct calorimetry inasmuch as the cabin of a spaceship is a natural calorimeter and it is necessary only to equip it with appropriate pickups for measuring the heat given off by a human or animal. In addition, the methods of mathematical analysis of the dynamic of vegetative functions during apportioned loads appear very promising to us. There is information on the presence of a definite relationship between a number of physiological functions and the state of metabolism and energy exchange. Let us recall, for instance, that practical medicine uses the empirical method of estimating body temperature according to pulse rate, and

conversely. The good correlation of pulse rate with the magnitude of energy expenditure is indicated in a large number of investigations [343, 617]. Pulse rate is proportional to body temperature and oxygen consumption during work [503], and the QT interval correlates with the magnitude of basal metabolism [491]. A disturbance of the exchange in the muscles can be established electromyographically [706]. An investigation of metabolism on the cellular level is of interest, inasmuch as gravitation changes can influence the conditions of translocation of nutrients and the elimination of waste material. Centrifuge experiments indicated that the rate of the metabolic process changes. Aircraft experiments studied the influence of brief weightlessness on amoeba activity. It was visually established that the speed of its movements increases, which indicates the influence of weightlessness on the metabolism and energy processes in a cell [650].

Digestion

The digestive process plays a leading role in providing constant augmentation of energy and building resources of an organism. In the digestive channel there occurs mechanical and chemical processing of food, and also suction.

Investigations of digestion under space flight conditions are very difficult in view of the inapplicability of the majority of known laboratory methods. Indeed, there exist proposals on the application Pavlov's fistula for studying digestion under flight conditions [400].

Quantitative methods of evaluating salivation and gastric secretion have been sufficiently developed. Moreover, the first experiment in telemetric transmission of physiological data [285] also involved the recording of the number of saliva drops of an experimental animal. There are methods for objectively recording the movements of the stomach and intestines with the aid of the methods of inductography [593], and electrogastrography [176], but the most promising is the application of endoradiosonde technique [614, 615, 425, 76, 46]. There are capsules for investigating temperature, pressure, and acidity, and also for determining hematemeses [562]. Probes have been described for studying hyperemia of the organs of the abdominal cavity [492]. Of much interest are the passive capsules which are twice as small as the conventional kind. This type of capsule works due to the energy of an external electromagnetic field, and the parameters of its oscillatory loop depend on the physiological parameters: e.g.,

temperature and pressure in the gastrointestinal tract [784, 787]. From the other methods we may mention the investigation of the reactions of the various systems of an organism in response to apportioned stimulations of the gastrointestinal tract. For instance, we know of hemodynamic shifts which occur as the result of mechanical stimulation of the stomach [158], after eating, and during meteorism. It is also possible to consider that the study of a number of vegetative functions, and also the energy balance of the body before and after the reception of apportioned food rations, can give answers to many questions concerning the state of the digestive function. It is possible that the development of methods of automatic analysis of waste products (urine and feces) with the creation of corresponding norms for eating foods of a specific composition would be expedient for space flight conditions. Finally, one of the possible methods of studying digestion in flight is electroplethysmography of the abdominal cavity, which makes it possible to estimate the movement of blood to the digestive organs.

Internal Secretion

The endocrine glands play a large role in the processes of regulating physiological functions. At the same time, these glands themselves are under the control of the central nervous system. The severe physical and nervous stresses that accompany space flight can lead to changes in the state of the endocrine glands. Thus, for instance, it is known that physical work and emotional stress cause an intensive release of adrenaline into the blood. Data have been published on the increase of adrenaline and noradrenaline in the blood during action of accelerations [470], and on the increase of the content of corticosterones in the urine of parachutists and pilots [41, 619]. Considerable changes in the function of the endocrine glands can lead to disturbances in normal activity of an organism, and consequently, to impairment of the tolerance to the factors of space flight.

In long-term space flights, a disturbance of the function of the endocrine glands can be the cause of various psychic disorders, changes in the energy balance of the organism, and a lowering in work capacity.

Two methods of investigating the function of the endocrine glands under space flight conditions are possible:

a) purposeful investigation of the various physiological functions with the clarification of symptom complexes which correspond to specific secretory

disturbances;

b) introduction of extracts from glands, or artificial preparations which correspond to them, with objective recording of the change of a number of physiological functions (pulse, [EEG] ([illegible]), [PV] ([illegible])).

Investigations on animals may employ surgical methods for the removal and transplantation of certain glands, followed by a study of the tolerance of these animals to the factors of space flight.

Neuroendocrine regulation of physiological functions, which is stipulated by the joint activity of the endocrine apparatun and the central nervous system, can be investigated by various methods. Thus, we developed a variational pulsometry method to estimate neuroendocrine regulation according to the state of the vegetative nervous system, which determines, in turn, the state of the function of cardiac automatism. Investigations on a denerved heart would make it possible to analyze the direct effect of endocrine influences that are transmitted by humoral means.

An interesting trend in research on neuroendocrine regulation of an organism is the study of biological rhythms. This problem is the subject of a significant number of works [298, 359, 495, 723], including research on daily cycling under the conditions of space flights [510, 740]. Biological processes have various rhythms: pulse and respiratory, daily and seasonal, those involved with a change in vascular tonus and with the oxygen content in the blood or synchronization of excitable formations. All these rhythms either directly depend on the state of the various neuroendocrine systems or are indirectly related to changes in the nervous and endocrine systems of the organism [161]. At present the search for new biological rhythms continues. The interest toward slow minute and hourly rhythms is great [623]. This interest is justified by the tendency to penetrate more deeply into the essence of biological processes. It is possible, however, to assume that there is a connection between the rhythms and activity of specific neuroendocrine systems. This opens up the prospect of establishing rhythms that correspond to specific neuroendocrine systems, and consequently, the possibility of objectively studying this complicated question in an integral organism under the conditions of space flight.

Analyzers

The inseparable relationship of an organism to its environment and its perfect "self-control" are based on the analysis of the influences rendered on the organism from the external and internal medium. The analyzer systems of animals and humans consist of three sections: receptor, conductor, and cortical. Signals proceeding from the receptors to the cortex of the cerebral hemispheres are subjectively perceived by man as sensations. Sensations are of much importance in the process of astronaut training and during space flight. They signal about the external world, ensure orientation in the environment, and make it possible to estimate the work of the motor apparatus. However, not all afferent signaling is perceived, and many reflector reactions can occur without the participation of consciousness. As an example, we may cite the vestibular analyzer, the stimulation of which causes various reactions that are both subjectively perceptible (nausea) and also imperceptible (quickening of pulse). There are extero- and interoreceptors.

In actual space flights, an especially large role belongs to the exteroreceptors. Intero- and exteroreceptors are interrelated through the nervous system as the links of a single receptor system of the organism. The methods of investigating the vestibular and motor analyzers were considered above. The methodological fundamental of the study of other analyzers obviously should be analogous (apportioned stimulation for the purpose of determining sensitivity, investigations on the character of functioning under a known working load, a study of the tolerance to maximum loads, and research on reflector reactions related to analyzer stimulation).

The skin analyzer analyzes signals from the tactile, temperature, and pain receptors. A decrease or increase in the sensitivity of the skin analyzer can lead to incorrect actions of the pilot-astronaut. Therefore, the determination of all forms of sensitivity is very important in the process of astronaut selection and in the pre-launch period. During flight, the stimulation of receptors can be evaluated by means of methods for recording galvanic skin responses, electroencephalography pulse tachometry, and others.

The visual analyzer plays an extremely important role in human life since more than 90% of all information about man's external world is obtained through the visual organ. A determination of the sensitivity and functioning of the visual organ under various loads is definitely necessary when selecting and training

astronauts. It is known that during the action of G-loads there can be observed a lowering in visual acuity, a disturbance in color sensation, and the appearance of amaurosis. Similar phenomena under flight conditions can disturb the orientation and work capacity of an astronaut. The state of the visual organ can be studied in flight with the use of the usual methods for determining visual acuity and color sensation as was done by the physician during the "Voskhod" flight. Indirect data can be obtained with the aid of electroencephalography, and electrooculography. It is necessary to study the problem concerning the applicability of electroretinography and methods of optical chronaximetry under space flight conditions, both adequate (P. O. Makarov) [298, 302] and inadequate (phosphine [26]). Conditioned reflex research methods also can be used [84].

The sound analyzer is very important in view of the necessity of conducting radio communications between the astronaut and Earth. An objective investigation of hearing can be conducted with the method of galvanic skin audiography [94] in which the threshold of perception is estimated on the basis of the appearance of a galvanic skin response. Electroencephalography may also be used. Conditioned reflex methods can detect changes related to the cortical section of the sound analyzer [171].

The taste and olfactory analyzers are of definite interest from the point of view of evaluating the general state of the receptor system of an organism [94]. They can be investigated by using stimuli and also by means of the chronaximetry method (for the taste analyzer). An important role can be played by the application of conditioned reflex methods.

In conclusion, we should also note the necessity of devising objective methods for investigating voice and speech, which is directly related to providing for reliable radio contact between an astronaut and Earth. Analyzers of the sound spectrum, and determination of the parameters of separate words can be used for this purpose: their duration, loudness, and frequency composition. The indirect analysis of speech can employ a number of other methods: e.g., pneumography and seismocardiography. Special methods for analyzing the speech process for purpose of creating systems for automatic speech identification have been developed by V. A. Kozhevnikov and L. A. Chistovich [145].

CONCLUSION

The principles of constructing physiological measurement and information systems, and the selection and development of physiological methods compose an important area in contemporary space biology and medicine. As follows from the materials discussed above, the development of this area essentially depends on the achievements made in space technology and in turn renders an influence on the organization and realization of flight experiments in space.

The experience gained as a result of conducting physiological measurements in single and group orbital flights up to five days in length has been extremely valuable both for a critical evaluation of everything that was accomplished and also for the theoretical and experimental development of problems concerning long-term and long-range flights.

At present, the development of physiological methods in astronautics has a very multifaceted character and can be considered in the following three aspects: technical, methodological, and naturally, physiological.

The technical aspect does not pertain completely to the prerogatives of engineers, although it is mainly involved with the development of pickups and equipment of measuring systems. In space physiology, probably earlier than in the other fields of science, it was required to establish a new type of collaboration between physicians and engineers. The physician activity participates in the discussion of all engineering problems, while the engineer takes part in medical problems. The extensive use of radio electronics, automation, and cybernetics to a considerable degree promoted the contact between physicians and engineers, while the stringent requirements imposed by space

technology to the physiological measurement system demanded the joint discussion and making of a number of compromising decisions, without which the realization of any in-flight research would have been impossible. The main trend in technical research in reference to the problems of space physiology at the present consists in improving the methods of collecting information, the creation new biotelemetry and radioelectronic devices with increased reliability and economy, the microminiaturization of equipment, the introduction of automation and computer technology, and the further development new, more improved designs for pickups, instruments, and measuring circuits.

The methodological aspect is related to the solution of problems of the optimization of physiological measurements in space. The main trend in methodological research is the search for the principles of constructing physiological measurement and information systems in reference to specific forms of flights. The correct selection of the measurement principle subsequently ensures the most effective utilization of spacecraft equipment and maximum research and diagnostic capabilities. It was shown that an increase in the duration and range of flights was related to the application of new principles of constructing a physiological measurement system.

At present it is possible with sufficient definitiveness to point out three basic types of physiological measurement and information systems:

1) for "Vostok" spacecraft and analogous flights;

2) for flights lasting from several weeks to several months (e.g., flights to the Moon and around the Moon), when most of the research, diagnostic, and medical work still can be carried out by a ground staff. These flights can take place both with the participation of a physician and also without him. The possibility of returning astronauts to Earth in periods from several hours to several days and the possibility of transmitting the necessary volume of medico-physiological data to Earth (with the application of automatic data processing systems) are important here.

3) for interplanetary flights, when the guiding principle is that of spacecraft autonomy and the Earth can render only consultational assistance to the on-board physician.

It is natural that under specific conditions there also can exist numerous transition types of physiological measurement and information systems. Moreover,

the isolation of these three basic types is quite tentative and ensues from the materials that have been accumulated to the present time. We do not exclude that a major reconsideration of a number of methodological principles will be demanded in view of the future progress of astronautics and the appearance of new problems. In particular, it is possible to expect the development of a special trend in physiological measurements in reference to human life support on the surface of the Moon and planets.

This requires, first of all, an investigation of the influence of flight factors on the human and animal organism; then there is the task of selecting (or devising) appropriate methods for conducting reliable medical monitoring and obtaining the information that is necessary for making a diagnosis.

Finally, it is no less important to expect possible disturbances, which requires the collection of the most diverse information on the state of man and other biological specimens (bioindicators) during flight. Thus, the physiological aspect includes three areas: research, diagnostic, and prognostic. These areas are closely interrelated to the most diverse problems of space physiology, and they are directly related to the majority of experimental and theoretical research that is conducted on Earth and in space. What kind of information is needed for the rapid manifestation of deviations in flight? What data must the physician have in order to make a diagnosis? What must be studied in order to make a prognosis? These and similar questions cannot be answered without taking into account the entire complex of data which is at the disposal of space biology and medicine. Without an answer to these questions, it is impossible to construct effective systems for physiological measurements in space flight.

In the final result, the main purpose of the application of physiological methods in astronautics is to provide the most optimum combination of man and spacecraft systems. The data obtained in the course of flight experiments make it possible to evaluate the state of an astronaut and, if necessary, to provide the necessary measures, right up to an energency return.

Postflight analysis of physiological information makes it possible to obtain the data necessary for the further development of theoretical and laboratory investigations, and then the formulation of new flight experiments.

In the future, physiological information will be able to be used directly on a spacecraft. The presence of on-board automatic processing systems will make it

possible to issue recommendations or even turn on devices for rendering assistance to the crew: e.g., emergency oxygen supply (biocontrol). Thus, the future tasks of physiological measurements in space flight involve the optimization of relationships in the "man-machine" system. The exchange of information in this system implies not only the obtainment of data from man, but also the opposite influence of the automatically processed information on the object of measurement.

In considering the physiological measurement and information system as a cybernetic system, and emphasizing the role of feedback, we enter the area of the methods of physiological research from strictly methodological problems to general methodological ones, and even philosophical questions related to the further development of space science. This approach makes it possible not to restrict research in this area to pickups, amplifying equipment, and individual methods. It makes it possible to consider the astronaut not only as a source of information, but also as the object of the influence of the control signals that are generated by the data analysis system. It makes it possible to consider the physician as the link in the physiological measurement system which provides for the optimum processing of information into control signals by means of direct participation in this process (on Earth or on board) or through on-board automatic devices which perform according to algorithms devised by the physician.

Scientific progress is possible only by means of the selective collection of mutually-comparable information. In this sense, the data obtained on Earth and in flight serve as a common goal, i.e., the expansion of our knowledge concerning the reactions of a living organism to the action of unusual factors and the guarantee of safe life support in outer space. A deepening of this idea leads to the necessity of analyzing numerous "terrestrial" situations with space methods, i.e., to the use of the physiological methods employed in astronautics for clinical and hospital research on Earth. Only with a similar method can we quickly collect the information needed for refining the methods of monitoring, research, and diagnostics in the forthcoming long-term and long-range flights.

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